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HC-130 Wing Life Raft Replacement Study

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16. Abstract

The U.S. Coast Guard (USCG) uses HC-130 aircraft for search and rescue (SAR) and other missions. The aircraft are presently equipped with two to four 20-person inflatable life rafts, stowed in cells in the wings. Similar rafts are also used for SAR missions, dropped to survivors from low altitude. The existing HC-130 wing life rafts are reversible, and rely primarily on a drogue both to reduce drift rates and provide some increased resistance to lifting out or capsizing. By contrast, several current designs of rafts, many of which are already in service as survival rafts for commercial ships and smaller craft, incorporate fabric ballast bags, attached below the buoyancy tubes. These bags are intended to rapidly flood with seawater once the raft is afloat. A prototype raft intended to serve as a replacement for the existing raft incorporates a ballast system of this type.

This report summarizes a general review of the available literature on life raft behavior in extreme wind and sea conditions. It emphasizes the underlying physical mechanisms of life raft capsizing, life raft resistance to capsize, raft drift forces and speeds, potential hazards to life raft occupants as a result of extreme motions and sea loads, including capsize in breaking waves, effects of extreme sea loads and unusual attitudes on life raft integrity, and stability criteria and related test requirements currently in effect. The report also summarizes observations made during acceptance tests (inflation, righting, and canopy erection tests) of the prototype HC-130 replacement raft, observations and measurements taken during sea-tests for comparison of existing and prototype rafts, and lift-out force tests in accordance with USCG proposed rules.

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METRIC CONVERSION FACTORS

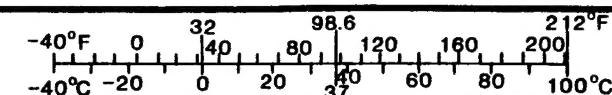
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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Nomenclature

A	effective area for windage or wave strike
B	raft breadth (for lift-out force test)
BM	metacentric radius (distance from center of buoyancy to metacenter)
D	raft depth
E_c	"capsize energy" (area under righting arm curve from upright to point of capsize)
E_r	"re-righting energy" (area under righting arm curve from inverted to point of re-righting)
F	raft freeboard
	lift-out force
GM	metacentric height (distance from center of gravity to metacenter)
H	effective lever arm for windage or wave strike couple
I_r	roll moment of inertia
L	raft length
N	measure of capsize resistance
P	rated number of persons for life raft
R	roll gyradius
V	displacement volume
W	total weight including ballast
α	non-dimensional capsize energy E_c/GM
ζ	wave height

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Executive Summary

The U.S. Coast Guard uses HC-130 aircraft for search and rescue (SAR) work and other missions. These aircraft range from 5 to 20 years in age, and are currently undergoing a Service Life Extension Program (SLEP), intended to enable their use for an additional 20 - 30 years of service. The aircraft are presently equipped with two to four 20-person inflatable life rafts, stowed in cells in the wings. Similar rafts are also used for SAR missions, dropped to survivors from low altitude.

The existing HC-130 wing life rafts are reversible, and rely primarily on a drogue both to reduce drift rates and provide some increased resistance to lifting out or capsizing. By contrast, several current designs of rafts, many of which are already in service as survival rafts for commercial ships and smaller craft, incorporate fabric ballast bags, attached below the buoyancy tubes. These bags are intended to rapidly flood with seawater once the raft is afloat. Adequately sized ballast bags have been shown to reduce the tendency of the raft to upend, lift out, or capsize. When applied in combination with adequately sized ballast bags, effective drogues have also been found to have a significant impact on raft motions and resistance to capsize under various conditions. A prototype raft incorporating ballast bags has been compared with the existing raft. The following main conclusions are reached:

(1) On the basis of comparative at-sea tests between the existing raft and a ballasted prototype raft, it is concluded that the prototype raft, unloaded, has significantly less drift, and would be easier for a swimming survivor to reach than the existing raft. The prototype raft rode more easily in pitch and roll, with or without a drogue, but reached essentially the same maximum angles as the old raft. The main effect of the drogue on the new raft is to hold it "head to sea." Even with drogues deployed, the existing raft is considered significantly more likely to capsize in severe seas than the prototype raft, especially if lightly loaded.

(2) A comprehensive, adequate, and validated theoretical or numerical predictive tool for inflatable life raft capsize under extreme conditions does not exist, and the current state of computational fluid dynamics is not likely to produce such a tool in the near future. The importance of raft stability, in the strict sense of restoring moment and its integral with respect to roll angle, is often overstated, while the importance of inertia to capsize resistance is not sufficiently emphasized. Life raft capsize occurs in the majority of cases due to interactions which are local to an individual wave crest, or the result of breakdown of a wave crest. These interactions may be characterized in most cases by: (a) encounter with a wave crest near the limit of breaking; (b) encounter with a spilling breaker; (c) encounter with a plunging breaker jet; (d) overturning on the interior of a large plunging breaker.

(3) An effective drogue is considered an adjunct to the raft' s stability and inertia, but not a substitute. In sea-tests performed as part of this study, the observation was made that drogue tension actually increased "kiting" and unstable airborne motions of the existing (unballasted) raft, when empty. Nevertheless, a drogue provides a counter-capsizing moment which increases with large inclinations, and a force which pulls the raft over or through the crest more quickly. This may reduce the time during which the raft is exposed to windage or breaking wave forces, and consequently the total capsizing impulse. A drogue also holds the raft "bow" to sea and/or wind.

(4) Drogues are considered less effective in confused seas, and where wind and waves may be from different directions. A drogue's effectiveness can be impaired by fouling in its own bridle, or by damage. Improved drogue designs exist which are more stable and less subject to snatching, tumbling, and bridle fouling.

(5) By contrast, ballast adds inertia in both angular modes, and remains effective in confused sea conditions. For a light unballasted raft, which is susceptible to being lifted out of the water by windage forces and moments, a drogue alone may not be sufficient to improve performance. Several sea test experiences have reported damage to large ballast bags and their attachments. No damage to ballast bags occurred during the sea tests reported here. Notwithstanding contradictory claims that have been made on all sides of the debate, there is no compelling reason to conclude that there are significant hazards to raft or personnel implicit in separately bagged, toroidal, or hemispherical ballast distributions, given good design.

(6) In 1994, the Coast Guard issued a Notice of Proposed Rulemaking for Inflatable Life Rafts (Federal Register, October 18, 1994, Department of Transportation, USCG, 46 CFR Parts 159 and 160). While this rule was never enacted, it required a raft to have a specified resistance against being lifted out of the water by a vertical force acting on one edge. While this test does not represent all mechanisms of capsize, it does provide a relative measure of the raft's initial righting moment. Lift-out tests were performed on both rafts, and showed that the prototype raft required lift-out forces on the order of ten times greater than the raft currently in use. FAA standards for U.S. aviation rafts do not include a lift-out force requirement, but they do require water pockets or other means to provide capsize resistance.

1. Introduction

The U.S. Coast Guard uses HC-130 aircraft for search and rescue work (SAR) and other missions. These aircraft range from 5 to 20 years in age, and are currently undergoing a Service Life Extension Program (SLEP), intended to enable their use for an additional 20 - 30 years of service. The aircraft are presently equipped with two to four 20-person inflatable life rafts, reversible, stowed in cells in the wings. These rafts have also been used for SAR missions, dropped to survivors from low altitude.

Under moderate to heavy sea and wind conditions, the existing rafts have been noted to "lift out," or "kite" off the surface, upending or capsizing repeatedly before they can be boarded. These responses appear to be produced mainly by a combination of wind and steep wave crests, which expose the raft body to lifting forces. Very energetic motions of the raft, combined with erratic drift, may increase the difficulties of survivors in reaching and boarding the rafts. Loaded life rafts also experience large amplitude motions in severe seas, which may potentially lead to capsize.

The existing HC-130 wing life rafts are reversible, and rely primarily on a drogue both to reduce drift rates and provide some increased resistance to lifting out or capsizing. By contrast, several current designs of rafts, many of which are already in service as survival rafts for commercial ships and smaller craft, incorporate fabric ballast bags, attached below the buoyancy tubes. These bags are intended to rapidly flood with seawater once the raft is afloat. Adequately sized ballast bags can reduce the tendency of the raft to upend, lift out, or capsize in several ways:

(1) By increasing the raft's inertia, reducing its responsiveness to sea or wind impulses.

(2) By providing a weight of water ballast acting on the elevated edge of the raft as it rises out of the water, consequently increasing the available righting moment and righting energy at large angles.

(3) By reducing emergence and maximum inclination angle, and consequently the magnitude of wind forces acting on the raft at a wave crest.

In addition to ballast bags, effective drogues have been found to have a significant impact on raft motions and resistance to capsize under various conditions.

The objectives of this study are as follows:

(1) To perform a general review of the available literature on life raft behavior in extreme wind and sea conditions, with a special emphasis on identifying the underlying physical mechanisms of life raft capsizing.

(2) To review theoretical and experimental means of defining and measuring life raft stability and resistance to capsize, under some of the circumstances that can lead to capsizing.

(3) To review methods of predicting and assessing the effects of canopies, ballast appendages, and drogues on life raft drift forces and drift speeds.

(4) To review available information on potential hazards to life raft occupants as a result of extreme motions and sea loads, including capsize in breaking waves.

(5) To review available information on the effects of extreme sea loads and unusual attitudes on life raft geometric integrity and buoyancy.

(6) To review the stability criteria and related test requirements currently mandated by various regulatory agencies and classification societies, in the U.S. and other nations.

(7) To observe acceptance tests (inflation, righting, and canopy erection) tests of a prototype replacement raft.

(8) To observe at sea-tests for comparison of existing and prototype rafts.

(9) To perform lift-out force tests in accordance with USCG proposed rules (Reference 4).

2. APPROACH

The approach to accomplishing this task order included a review of technical literature, observation of inflation tests, simultaneous at-sea tests for comparison of the existing HC-130 wing life raft and a prototype raft of recent design, and a lift-out force test as prescribed by the "Proposed Rule for Inflatable Life rafts,"; Federal Register, October 18, 1994, Dept. of Transportation, USCG, 46 CFR Parts 159 and 160.

2.1. Literature Review

JJMA performed a broad search of available technical literature, theoretical and applied, on life raft technology, focusing on inflatable rafts. The list of literature items reviewed is given in the Reference section of this report. The literature search was augmented by direct telephone communications with commercial life raft suppliers and government authorities in this field.

2.2. Contacts with U.S. Navy Activities

The cognizant activity for U.S. Navy aircraft life raft acquisition and product support is NAVAIR Code PMA 202 -- Aircrew Systems. Mr. William Naughton, PMA 202 DPM for Product Support, indicated that NAVAIR is not currently active in product improvements or fundamental research in the area of life raft stability against capsize.

The cognizant activity for U.S. Navy shipboard life raft acquisition is NAVSEA Code 03W21 -- Cargo Handling and Landing Craft/Vehicle Support. In the past, some supporting technical work in the life raft development area has been performed at the Combat Systems Engineering Station (NAVSEACOMBATSYSENGSTA) Norfolk, formerly designated NAVSEASYSCOMDET - Norfolk. Mr. Ronald Smith of 03W21 indicated that although his branch is presently supporting development of a new large life raft (50-person capacity), there is no research activity currently underway in the area of life raft stability against capsize.

2.3. Contacts with Federal Aviation Administration (FAA)

The Federal Aviation Administration (FAA) is responsible for promulgating requirements for life rafts and similar appliances, such as buoyant evacuation slides, carried by commercial and general aviation aircraft. Mr. John Petrakis of the FAA Engineering Division indicated that the construction and performance requirements for FAA-qualification of life rafts are presently limited to those contained in Technical Standard Order TSO-C70a, Life rafts (Reversible and Non-Reversible). This TSO, and other FAA requirements contained in 49 CFR 178, have been reviewed. General design and performance criteria related to stability and, by extension, resistance to capsize are contained in TSO-C70a. However, the requirements of TSO-C70a do not involve any specific measured data. These requirements have been reviewed, and are discussed in Appendix A.

2.4. Contacts with Governmental Agencies of Other Countries

Telephone contacts were made with maritime agencies of other countries, including:

- Australian Maritime Safety Authority
- British Maritime Safety Agency
- Transport Canada
- Norwegian Maritime Directorate
- DNV Oslo
- DNV North America

The interviews with these agencies were primarily devoted to understanding test and evaluation procedures for life rafts, placing primary emphasis on life raft stability under extreme conditions, and drift rate measurements and means for reducing drift. The interviewees were asked to identify their current design specification requirements in the areas of life raft stability against capsize, and also whether any extension of current criteria or proposed new criteria are presently under development.

In particular, the interviewees were asked whether consideration is being given to stability criteria which explicitly include windage forces and overturning moments, forces and moments imposed by breaking wave crests, or asymmetric occupant loading.

Without exception, the maritime agencies listed above did not provide specific answers in these areas: they stated that their approval of life rafts is in accordance with the requirements of Chapter III of SOLAS 1974 (as amended through Consolidated Edition 1997). Regulation 39/5 of SOLAS, Stability of inflatable life rafts, requires the following:

> 5.1 Every inflatable life raft shall be so constructed that, when fully inflated and floating with the canopy uppermost, it is stable in a seaway.
>
> 5.2 The stability of the life raft when in the inverted position shall be such that in can be righted in calm water by one person.
>
> 5.3 The stability of the life raft when loaded with its full complement of persons and equipment shall be such that it can be towed at speeds of up to 3 knots in calm water.

Interpretation of the phrase "stable in a seaway" is problematic. There is no requirement for a lift-out test. However, the so-called UK/Icelandic ballast system (discussed in References 31 and 32) has been considered one acceptable interpretation of adequacy. This system typically incorporates ballast enclosures containing a minimum of 0.02 m^3 (0.71 ft^3, or about 45 lb of

seawater) times the number of occupants for which the raft is rated. Generally, the system incorporates at least 5 separate ballast bags. These are essentially uniformly distributed around the perimeter of the raft, except that the inflation bottle may occupy a gap in the distribution of bags.

Tests for evaluation are carried out in accordance with the requirements of IMO Resolution A. 689(17), Testing of Life Saving Appliances.

2.5. Contacts with Life Raft Manufacturers

Telephone interviews were conducted with thirteen U.S. life raft manufacturers and distributors. Most of the manufacturers and distributors stated that the specific technical information or data requested, with regard to testing and design, are considered company confidential. Some, however, did provide technical data and sketch-quality drawings of their rafts. None of the manufacturers provided engineering drawings of sufficient detail to estimate static or dynamic stability, moments of inertia, windage or water drag coefficients, lift coefficients, or the resultant overturning moments.

In a commercially sensitive area such as product design, especially where product safety is an issue -- in fact, the central issue -- information obtained through informal contacts with suppliers is understandably subject to some bias. In interviews, as well as in some of the commercial literature, arguments regarding the superiority of one form of stability appendage over another are occasionally overstated, sometimes to the point of generating more heat than light.

The results of contacts with manufacturers were essentially non-technical. It appears that raft design is almost entirely empirical, cut and try. Resistance to capsize is understood on a pragmatic level, supported mainly by anecdotal data.

As will be discussed below, the effects on life raft capsize behavior, for which there are technical grounds to expect systematic differences from various ballast or ballast and drogue configurations, are not uniformly favorable to any one arrangement. In some cases, the phenomena which govern are not sufficiently well modeled to support a clear preference. Potential technical differences will be addressed in subsequent sections, together with a critical review of the available data, theoretical background where applicable, and possible avenues for obtaining additional resolution.

2.6. Raft Acceptance Tests

The prototype replacement raft is a 20-man SAR raft, manufactured by the Switlik Parachute Company, of Trenton NJ. Raft acceptance tests witnessed by JJMA included inflation tests and a manual righting test (required for non-reversible rafts), and a canopy erection test. A videotape of the acceptance tests is available from the USCG R&D Center.

2.7. Raft At-Sea Tests

Simultaneous at-sea tests were conducted on both the reversible and prototype replacement (water ballasted) rafts off San Francisco, 27 March 1997. Tests were conducted with and without drogues, and with the rafts empty and loaded, representing the additional weight of ten occupants. Drift rates, raft motion responses, and capsize behavior were observed. A videotape of the sea tests is available from the USCG R&D Center.

2.8. Lift-Out Force Tests

Lift-out force tests in accordance with Reference 4 were conducted on both the reversible and prototype replacement (water ballasted) rafts in Annandale, Virginia, during June and July 1997.

3. LIFE RAFT CAPSIZE

For a number of reasons, the analysis of an inflatable life raft's responses in extreme seas is substantially more complex than conventional naval architectural "seakeeping analysis," as it is usually applied to ships or small craft. For the analysis of capsize behavior, and even the comparison of alternative raft geometries, the limitations of conventional design practice are apparent from the following:

(a) The phenomena of critical importance are, by definition, extremely large roll and pitch angles.

(b) Test data and field experience has shown that such extreme attitudes, for ballasted rafts, are generally produced only by encounters with breaking waves which can be several times higher than the raft's characteristic body dimensions.

(c) The life raft's geometry is subject to large deformations in response to sea loads. Consequently, the usual assumptions of a rigid body geometry (even for the fundamental purposes of calculating hydrostatic and hydrodynamic forces) are obviously violated.

(d) The flexural characteristics of the raft are dependent on inflation pressure as well as tube diameter and geometry. Under a bending load, for example, raft tubes tend to buckle, as observed during lift-out tests. The bending load at which buckling is initiated is affected by inflation pressure. Although the raft returns to nominal shape when the bending load is removed, the distortions reduce the stiffness of the raft in the buckled condition, as well as changing the hydrostatics.

(e) The inertia and weight distributions represented by live loads (such as occupants) represent significant fractions of the total system. In principle, the behavior of a raft during capsize, and during subsequent re-righting, cannot be considered independently of the large-scale movements of the occupants, or their restraints against such movement.

(f) The inertial forces imposed on the raft by the presence of large water-ballast filled appendages, which represent a substantial portion of the total mass of the system, are extremely complicated. Not only are these water-filled appendages non-rigid -- they are not even necessarily of constant volume -- but the ballast, depending on its arrangement, is also subject to internal flow in response to raft motions and accelerations.

(g) The dynamic responses of the raft are significantly affected by the presence of an external drogue.

As a result of these considerations, the simplifying assumptions used in conventional seakeeping analyses are, almost without exception, untenable. For this reason, the analysis of sea loads and motions of an inflatable raft in extreme conditions, and especially responses leading to potential capsize, is significantly beyond the range of applicability of conventional naval architectural tools. In fact, as the review of the relevant literature will show, the over-all problem

is beyond the practical limits (or at least the range of validation) of even advanced numerical flow codes.

With regard to model testing, because of the dependence on material flexural characteristics and inflation pressures, even model tests, other than at quite large scale, would be of debatable value. At large model scale or full scale, waves of the type and size to represent capsize threats encountered at sea would be beyond the capabilities of most, if not all, experimental tanks. Therefore, the controlled experimental data necessary even to validate advanced numerical work would be quite difficult to acquire.

Rather than simply abandoning the field in despair, however, a theoretical and empirical groundwork for full-scale testing and evaluation of life rafts, using controlled experiments to determine certain characteristics, and at-sea testing for others, has been laid. This background, together with side-by-side at-sea testing of the prototype HC-130 replacement life raft and the existing raft, makes it possible to propose analyses and tests that serve to improve the state of life raft survivability in extreme sea conditions.

3.1. Stability and Resistance to Capsize

Capsize (vi & vt) [Origin unknown] To overturn or cause to overturn.
Stability (n) [From Latin *stabilis*] The quality of resisting change of position or condition.

---Webster's

In engineering the problem of over-simplified usage is that it may tend to obscure rather than clarify. This review focuses on understanding the capsize behavior of life rafts, the mechanisms of capsizing in extreme conditions, and identifying raft configurations and features that enhance resistance to capsizing and over-all survivability in the event of capsizing.

It is unfortunate that the term "stability" has often been used (mostly in the semi-technical literature, and in vendor advertising materials) as a catch-all -- to encompass the entire range of physical characteristics that are important in determining the ability of a raft to survive capsizing hazards.

"Stability," in naval architectural usage, is a description of a craft's equilibrium and restoring forces or moments, (that is, static stability). The term is also used to describe the work required to change a craft's attitude by a certain amount (dynamic stability). From the designer's standpoint, stability is a most important element in survivability. The form of the restoring moment as a function of inclination, or its integral with respect to inclination, can determine the response of a craft to overturning moments to a very great extent.

However, the popular use of the word "stability" to indicate something beyond these formal definitions, such as the over-all ability of a craft to avoid large amplitude excursions in attitude, has not been helpful in developing an understanding of capsize phenomena. In fact,

identifying increased stability, alone, with over-all resistance to capsize is somewhat akin to identifying large stability with good seakeeping qualities. They are not the same things. Stability is a static or quasi-static number (even so-called dynamic stability is merely the integral of static stability over a range of angles). Time is not involved.

In an extreme example of one capsize mechanism, riding the interior surface of a large plunging breaker, capsize occurs because the raft tends to remain "upright" with respect to a local normal to the water surface. This tendency is actually produced by large initial stability. A body with less initial stability would generally tend to remain more nearly upright with respect to the earth during the wave encounter. In this sense, it can be observed that it is the craft' s own "stability" which provides a major part of the moment to overturn it. A nearly neutrally stable body with large inertia would experience less inclination during such an encounter

The important point is that a raft's resistance to change in attitude may be conferred by restoring moments (stability, in a strict sense), by inertia, or by design features which reduce overturning moments of various kinds. In general, ballast arrangements affect both stability and inertia. The differences between specific ballast distribution arrangements (for example, a continuous toroidal chamber, or a series of interrupted ballast bags, located around the perimeter of the raft, or a large hemispherical bag) exist not only in stability, which is usually the major identified difference, but in mass and moments of inertia as well.

As addressed in the next sections, depending on circumstances, raft capsizing forces and moments may be applied with widely varying time scales:

- Steady or quasi-steady -- such as windage and underwater drag in "slowly " varying velocity fields.

- Rapid variation -- for example, the change in buoyancy, static moments, and wind forces and moments experienced during the passage of a sharp-crested but non-breaking wave.

- Impulsive loads -- for example, a breaking wave "strike," that is, an encounter with the face of the turbulent downslope flow on the face of a spilling breaker, or with the jet of a plunging breaker.

In each of these scales, the relative importance of stability and inertia in over-all resistance to capsize is different.

3.2. Capsizing Mechanisms

Several distinctive capsizing mechanisms can be identified under various circumstances, for bodies of different sizes. Some of the phenomena listed below, either by inspection or a rough calculation, will be shown to be of little or no importance for typical inflatable life rafts:

(a) Synchronous roll in waves, typically experienced by vessels in beam or quartering seas with forward speed. (Synchronous roll results from a wave encounter frequency which coincides with the natural roll frequency of the body.)

(b) Roll instability caused by cyclic reductions in righting moment due to changes in waterplane inertia during vertical plane relative motions, occasionally experienced by ships with low statical stability during the passage of the crest of a sea.

(c) Forces imposed by attempts to maneuver or propel the raft.

(d) Extreme wind loads (often with heavy gusts overlaid on a high sustained wind speed) in addition to, but considered essentially independently of, wave induced roll.

(e) Asymmetric loading, or shifting of cargo or passengers..

(f) Free surface of water in the raft's body.

(g) Transient forces and moments, both hydrodynamic and wind-induced, occurring during passage over the crest of a sharp-crested (that is, a limit non-breaking) wave.

(h) Forces and overturning moments due to impact with the front of a spilling breaker, or the jet of a plunging breaker.

(i) Overturning due to riding the interior surface of a large plunging breaker.

Some observations regarding the importance of these capsizing mechanisms for life rafts are given in the following sections.

3.2.1. Synchronous Roll

Synchronous rolling occurs when the roll natural frequency equals the wave exciting frequency, resulting in large amplitude resonant response. Capsizing due to synchronous roll alone is generally not an issue for life rafts. For an unballasted raft of typical proportions (with a wide or nearly circular planform and very shallow draft) the natural period of roll is far too short to be excited by the predominant wave frequencies in any seastate energetic enough to present a hazard. (A typical 10 ft diameter raft, for example, approximately a 20-person capacity, has a

natural roll period of approximately 1-2 seconds, fully loaded. The flat bottomed, shallow form is also extremely heavily damped, which limits the response amplitude even at resonance.)

For a water-ballasted raft, the deeper underwater form and consequent changes in stiffness (restoring moment) and inertia in roll influence the roll period in various ways. When the ballast is an additional enclosed volume of seawater located below the raft's buoyancy rings, the initial roll stiffness (proportional to total weight W including ballast, times metacentric height GM) is unchanged from a "flat-raft" of equivalent diameter. This is clear because the presence of the ballast makes exactly the same contribution to both weight and buoyancy forces, acting at the same centroid. The roll stiffness actually increases very slightly due to the weight of the ballast bag itself, but this is negligible in comparison with the ballast water contained.

While water ballast added below the raft body, does nothing to initial restoring moments, it can have major effects on the range of stability, righting energy, and moments of inertia. The effect on roll moment of inertia is more complicated than it might appear at first glance. It would be convenient to consider the inertial effect of ballast as if it were simply a massive and rigid addition to the raft's own intrinsic moment of inertia, neglecting internal flow inside the ballast bag(s). With this assumption, the addition of ballast bags can increase the inertia of a loaded raft significantly, depending on the geometry and amount of the ballast and the assumed distribution of mass in the raft.

For a loaded life raft, most of the mass, other than water ballast, is due to the occupants. Since roll period varies approximately as the square root of the moment of inertia, even a large change in inertia may not change the raft's natural period significantly. An example may illustrate this. Consider a hypothetical 10 ft diameter circular life raft, weighing 200 lb equipped, with ten 160-lb occupants. Six ballast bags are attached around the perimeter, each enclosing 180 lb of seawater.

In order to assess the contributions to moment of inertia, the buoyancy tubes are taken as 1 ft in diameter each. The mass of the water ballast is modeled as a hollow cylinder of diameters 9.5 ft outside and 8.0 ft inside, 1.25 ft deep. The occupants are distributed uniformly around the ring, with their backs to the buoyancy tubes. Their mass is also modeled as cylindrical distribution, with diameters 8 ft outside and 6.75 ft inside, 2.5 ft deep.

Approximate inertias about a diameter of the raft through the CG are summarized in Tables 1 and 2.

Table 1. Effect of Water Ballast Bags on Moment of Inertia

Item	Weight (lb)	CG above Raft Floor (ft)	Figure Moment of Inertia (sl-ft^2)	Moment of Inertia due to Vertical Location (sl-ft^2)
No Seawater Ballast				
Raft Tubes	150	1.00	49.3	0.2
Remainder of Empty Raft	50	1.50	6.2	0.2
Occupants	1600	1.20	366.4	0.0
	1800	1.19	421.9	0.4
			0.4	

Unballasted Raft (Loaded)	1800	1.19	422.3	
With Seawater Ballast				
Unballasted Raft (Loaded)	1800	1.19	422.3	25.9
Seawater Ballast	1080	- 0.63	328.0	43.6
	2880	0.51	750.3	69.5
			69.5	

Ballasted Raft (Loaded)	2880	0.51	819.8	

With the seawater ballast essentially doubling the moment of inertia of the loaded raft, it can be seen that a life raft which increases its roll period from 2 seconds to 3 seconds (as the square root of inertia) would remain a quick roller by comparison with typical sea wave periods.

Even for an unrealistically large hemispherical ballast bag attached to the same raft body, the following comparisons are shown:

Table 2. Effect of Hemispherical Ballast Bag on Moment of Inertia

Item	Weight (lb)	CG above Raft Floor (ft)	Figure Moment of Inertia (sl-ft^2)	Moment of Inertia due to Vertical Location (sl-ft^2)
With Seawater Ballast				
Unballasted Raft (Loaded)	1800	1.19	421.9	275.7
Seawater Ballast	8580	- 1.50	1106.7	58.9
	10380	-1.03	1528.6	334.6
			334.6	

			1863.2	

This inertia is approximately 4.4 times the unballasted raft. Nevertheless the resulting period of 4 seconds would not be sufficient to produce synchronous roll with reasonable wave conditions.

Moreover, there are a number of reasons why such a large contribution to inertia will not arise in reality. First, seawater enclosed in a ballast bag by no means contributes inertia as if it were a rigid body. Even if the ballast bag were considered as a rigid shell, which is obviously far from the case, the enclosed water ballast would not act as a rigid body, in terms of angular inertia, under an oscillatory acceleration. Unless it is constrained by internal compartmentation or baffles, the ballast will not accelerate in phase with the raft, or with as high a value of the maximum acceleration, even if the boundary of the ballast compartment were rigid. It should be anticipated that the effective added inertia of ballast water, when it is free to develop gross oscillatory internal flow, would be considerably less than that of an equivalent distribution of mass capable of angular acceleration as a rigid body. The larger the volume and cross-section of the ballast bag, the further the situation will be from that of a rigid body inertia.

Second, the effective inertia of a floating body includes not only its intrinsic inertia (in air), but also the so-called added inertia, a hydrodynamic force due to the acceleration of the fluid surrounding the body. At low frequency, the added inertia of a flat raft (considered as a rigid body) is approximately 1/3 of the inertia a hemisphere of fluid of the same diameter. Consequently, the over-all effect of a large ballast bag on a raft's natural roll period is not necessarily as large as it would appear from the inertia in air.

By contrast, for a segmented set of peripheral ballast bags, or a toroidal arrangement with internal baffles, the effects on roll inertia should more closely resemble those found by rigid body dynamics, although the deformation of the ballast bags under oscillatory motions would tend to reduce their contribution.

With regard to damping and excitation, it should be anticipated, in the absence of detailed computations or tests, that the damping and excitation of a raft with flexible ballast bags would not be very much different from a flat raft of similar size. In general, gross deformations of a body under loads tend to reduce damping, and roll excitation, although the effects of large deformations cannot be calculated by current methods. It may be speculated also that flexure of the raft, when resisted by interactions with the raft's live load, could either tend to excite or damp roll, depending on phase. These effects have not been measured experimentally, or observed in tests, and are expected to be relatively unimportant.

As a general conclusion, the natural roll period of a ballasted raft is expected to be somewhat longer than for a flat raft of similar diameter, and the damping slightly less. Nevertheless, on the basis of very rough estimates, large differences in over-all rolling behavior are not expected, and dramatic differences in sea behavior have not in fact been noted in the literature. The over-all inference is that pure synchronous roll is not an important mechanism of capsize for life rafts of typical forms, ballasted or not.

3.2.2. Parametric Instability

As a wave profile passes along the length of a vessel, the vessel's instantaneous waterline changes, and therefore, so does its metacentric height. The result is that considerable variation in GM occurs, with a frequency equal to the encounter frequency. At certain critical frequencies, this parametric variation can lead to unstable rolling, in spite of the fact that the vessel shows adequate stability as measured by static criteria. The result is a growing roll angle developing in waves which are neither extremely steep, nor breaking. (Reference 34)

Parametric instability arises, typically, for ships having low initial stability in conditions of low frequency of encounter, such as in stern or following seas, with speed. Parametric instability does not occur for life rafts, for several reasons: First, the life raft is of quite small dimensions with respect to typical wavelengths, and consequently the deviation of the surface of a (non-breaking) wave from a plane, over the raft's dimensions, is for practical purposes negligible. Second, life rafts, whether ballasted or not, are characterized by high initial stability. Finally, being craft of very low speed, life rafts typically are not subjected to waves at very low encounter frequency.

3.2.3. Capsizing due to Maneuvering and Propulsive Loads

Under its own limited power, that is, the manual power of its occupants, paddling, a normally sized and proportioned life raft is clearly incapable of being maneuvered or propelled forcefully enough to present a hazard of capsizing. However, if improperly handled when under tow, a life raft can be upset by excessive forces or moments, or swamped by excessive towing speed.

Towing is generally considered a more important issue for shipboard life rafts, which would be more likely to have to be towed out of a dangerous situation by a self-propelled lifeboat or rescue boat, than for an aircraft life raft. This is particularly the case when the objective is to tow a raft clear of a fire hazard, such as an oil spill, or debris or "suction" generated by a sinking vessel. By contrast, for aircraft survivors, mobility is almost universally considered as a secondary issue to drift limitation for search and rescue (SAR) purposes.

However, there may be certain specific situations, perhaps quite distinct from the circumstances of a ditching or SAR operation far from land, in which safe towing of a raft may become important for rescue of personnel.

The operational solution to reduce capsize risk is proper handling and prudent towing speed. From the design standpoint, in general, the towing behavior and speed capabilities of a raft are improved by rigging the bridle to attachment points relatively low on the raft body, approximately at the height of the center of drag of the underwater body.

For a heavily water-ballasted raft, the center of drag is somewhat lower than on a flat raft, but the difference is not necessarily as great as the centroids of the respective (nominal) frontal areas would suggest. The center of drag is also not constant with speed, when the elevation and

pressure field in the "bow wave" is considered. Although towing speeds for life rafts are necessarily fairly low, the bluff body of a raft produces a significant rise in pressure, reflected by elevation of the free surface.

Uncertainties in drag and moment could be lessened, to some extent, by model testing. However, the deflection of a non-rigid ballast bag due to speed through the water could be significant, and would produce some change in drag and moments. Consequently, towing experiments at model scale must be regarded with a certain amount of caution.

Deballasting Arrangements. In some situations there could be an operational desire to reduce the drag (and increase the available towing speed) by emptying some or all of the ballast. Therefore, the convenience and reliability of various features to release the ballast for towing should be considered. As pointed out in Reference 10, ballast release arrangements have failed in the past. In general, the behavior of a raft under tow, with and without ballast water, and consequent operator guidance for safe ballast release procedures and towing speeds, should be made available to users, perhaps even going so far as to provide such guidance in the form of a placard in the raft.

3.2.4. Capsizing by Wind Forces and Moments

A dangerous source of instability for a life raft is the momentary loss of static righting arm when it becomes unweighted, either by the acceleration of the free surface itself, at the crest of a wave, by becoming partially "lifted-out" by aerodynamic forces, or by a combination of the two. This behavior is only to be found in extreme waves, either steep or breaking, and generally with high winds, and cannot be considered as parametric instability.

Under the simplifying assumption that wind forces and moments can be considered independently of waves (which, as discussed below, is an assumption of problematic accuracy for life rafts) the mechanism of capsizing by wind alone is sufficiently well understood. The classical approach to assessing stability against capsize by wind alone involves the determination of two parameters, and comparison against criteria for acceptable safety:

- The equilibrium heel angle at an assumed criterion wind speed.
- The excess of righting energy over heeling energy from an assumed initial angle to the point of capsize.

For ships and small craft, it is the customary practice to determine these parameters in a rather simplified way, namely, with the following assumptions:

(1) That the heeling arm due to wind forces follows a cosine-squared dependency with inclination, at least for the range of inclination angles of interest.

(2) That there is no significant vertical component of wind forces tending to lift the hull bodily out of the water (which would consequently reduce the available hydrostatic restoring moments).

(3) That the wind is applied as a steady or quasi-steady force and moment (and consequently that dynamic responses due to gusts do not play a significant role).

Both theory and detailed experimental data exists which demonstrates that the first two of these assumptions are substantially <u>incorrect for rafts</u>. (For example, see References 12 and 13.) Because of its wide and shallow form, the wind heeling arm of a flat raft increases with inclination, often quite dramatically. A ballasted raft with a "hollow" bottom which is capable of stagnating a large portion of the air flow under the raft (a feature which can be formed by a toroidal ballast enclosure after emergence of part of the upwind edge) may experience an even larger heeling arm. Further, the vertical lift coefficients measured in experiments are significant, particularly for flat rafts and "hollow-bottomed" ballast arrangements.

For real rafts, the ability of wind pressure to deform the canopy or raft body may actually <u>increase</u> the drag and lift beyond the values obtained in wind tunnel tests with relatively rigid models. With regard to raft dynamic responses to gusts, no published experimental data has been found.

The over-all conclusion of independent experiments (References 12 and 13, for example) supports the notion that with regard to wind forces and moments, a spherical ballast enclosure, or at least an underbody shape which does not tend to stagnate the flow under the raft when the upwind edge becomes emerged, is an advantage. However, with a toroidal ballast arrangement, which would presumably be susceptible to this effect, the actual conditions under which the lower edge of the ballast bag would emerge as a result of wind or waves, and lead to increased dynamic pressures under the raft, have not been established.

It may be speculated that a deep toroidal bag would not emerge its lower edge as frequently as a shallow one, but that its emergence would be initiated at a higher inclination angle, and consequently with a more abrupt change in lift and drag forces. As a result, the magnitude of any presumed advantage of a spherical underbody over a toroidal arrangement, in terms of the likelihood of capsizing, is uncertain. It should be noted that heavily ballasted rafts, whether of the hemispherical, separate bag, or toroidal ballast configurations, have not been capsized in tests by pure windage alone.

The total impulse imparted by windage effects during the interval while a raft passes over a discontinuity in free surface slope (such as at the crest of a sharp-crested wave), have not been evaluated in any detail, either numerically or experimentally. However, there is reason to believe, on the basis of at-sea tests, that the effect is not small. It can be assumed that the average wind velocity near the surface is essentially parallel to the local surface of the wave. The discontinuity at the crest produces a sudden increase in both the exposure of the raft's undersurface, possible emergence of the lower edge (of a toroidal ballast bag), and a greater local angle of attack for the

wind as the raft passes over the crest. The magnitude of this effect has not been measured experimentally.

Estimates made on the basis of wind tunnel results (Reference 12) with an inclined raft embedded in a flat ground-board, even at an assumed 60-deg inclination angle corresponding to the shape of a sharp-crested wave, do not include the spatial effects of discontinuity in the air flow over an actual crest, nor would they include unsteady effects.

While no incidents of a heavily ballasted raft actually overturning due to windage at a sharp crest, even in the unloaded condition, were observed during the sea tests reported in section 5, below, life rafts have often been recovered overturned after severe storms (References 10, 31, and 32). However, in most cases it has not been possible to determine the precise mechanism of raft overturning unless the capsize event is actually observed.

3.2.4.1. Wind Capsize as the Basis for the Lift-Out Force Test

A lift-out force test, as described in Reference 17, is an effort to compare rafts on the basis of a relatively simple measurement, namely, the force required to lift one edge of the raft vertically from the water surface at a prescribed rate. This test requirement was withdrawn following the adoption of SOLAS regulations for life rafts. Nevertheless, the lift-out force test illustrates several factors of real or perceived importance in considering life raft capsize. Therefore, despite the fact that the proposed rule requirement was withdrawn, the elements of the lift-out force test are worthy of consideration.

Capsizing by windage was the original argument leading to the use of the lift-out test as a measure of capsize resistance. It is supposed that the raft (or at least its upwind edge) must be lifted out of the water as a pre-condition for capsize. If this premise is accepted, it could be argued that a direct experimental measurement of the resistance of the raft <u>against being lifted out</u> would give a very general measure of over-all resistance to capsize. The problem with this inference is that it follows from definitions rather than from dynamics. In most capsizes (and there are exceptions that will be pointed out below), an edge of the raft will have to rise out of the water at some point, by definition. However, this fact is not considered conclusive with regard to cause and effect.

The geometry of the forces applied in a lift-out test follow from the assumption that "lift-out" is the most important (or at least the most identifiable) feature of the capsize process. This appears to be true in a windage capsize. However, the philosophical flaw is to associate <u>all</u> capsizing moments with the lift-out force, and then to state lift-out force criteria, for rule and approval purposes, solely in terms of an assumed wind speed and associated aerodynamic drag, lift, and moment data. There are certainly mechanisms for capsize, including those that act in breaking waves, which do <u>not</u> require lift-out as pre-cursor for capsize (even though emergence of the edge of the raft would occur concurrently or as a consequence of capsize). As stated above, with a heavily ballasted raft, capsize by windage alone has not been directly observed.

3.2.4.2. Comments on the Lift-Out Force Test

General Comments. As presently specified in the 1994 Notice of Proposed Rule Making (NPRM) (Reference 19), the lift-out force is confined to moderate angles of inclination. The lifting bridle must be hoisted through a distance of at least B sin 20°, where B is the raft breadth (or diameter of an essentially circular raft). Consequently, the maximum required inclination of a rigid raft would not materially exceed 20 deg in this test. For a raft which deforms, the effective inclination may not even reach 20 deg, while the local slope at the lifted end exceeds 20 deg.

The test places a high premium on the raft's weight, including the weight of ballast water lifted above the surrounding water surface, retention of ballast during lift-out, and the rigidity of the raft. A heavy raft with a large ballast capacity will give a large lift-out force, provided that its structure is sufficiently rigid to transmit loads to the lifting point. This emphasis on measuring the weight and ballast retention of the raft, to the exclusion of other capsize-resisting quantities, is a limitation in terms of predicting various type of capsize. In particular, with a constant lifting rate there is no acceleration and consequently no direct indication of the raft's roll inertia. Further, there is no criterion for inertia. This point will be returned to in connection with capsizing in breaking waves.

Hoisting Rates. There is an error in the specified hoisting rate given in the draft of the 1994 NPRM, in Rule 160.151-29(a), paragraph (6). If the raft breadth B is given in ft, the hoisting rate is required to be 5.5 B (ft/min). If the raft breadth is given in meters, the hoisting rate is required to be 1.67 B (m/min). There is an inadvertent double application of the conversion factor of m to feet. The true requirement is 5.5 B ft/min, with B in ft, based on the rates used in Reference 17. A correct way of stating the rate, regardless of the units used, is that the raft must be lifted at a rate of 5.5 raft breadths per minute.

Because water retention in the ballast bags is an important element in the lift-out force result, it has been seen that faster lift-out rates result in increased maximum forces. For this reason, since the acceptance criterion is stated as a minimum acceptable force, with no maximum limit, the performance of the test would be made considerably less difficult by removing the lower limit from the rate and simply stating that the hoisting rate "shall not be greater than 5.5 B per minute."

Hoisting Time. For a total hoist distance and hoisting rate that are both proportional to the dimension B, it is the hoisting time which is invariant with respect to raft size. In effect, the specified tolerance of plus or minus 5 percent on the required hoisting rate means that the bridle must be lifted through a vertical distance of B sin 20° in a time of 3.5 sec (minimum) to 3.9 sec (maximum).

The implication of a constant time to reach the stated hoist height, independent of raft size, is that it is based on a time-characteristic (perhaps of the environment itself) which is the same for all rafts, such as the typical rise-time of a gust load or other rapidly applied load. Constant time does not address any particular scaling for accelerations.

Rate Dependent Forces. Because the lift-out test is performed with a nominal speed of emergence, the potential sources of rate dependent forces should be understood. Rate dependent forces are judged to be an important element in life raft capsize.

Drainage of Ballast. For water ballasted rafts, a main source of rate dependence is drainage of the ballast bags as they are lifted out of the water. Retention of ballast water during the test clearly increases the lift-out force. Drainage occurs in several distinct ways, including the following:

(1) Ballast bags empty through the filling openings, as the shape of the bag changes during lift-out (pumping).
(2) The fabric of the bag may be permeable, either through selection of a porous material, or if a bag has been scuffed or damaged.
(3) Seams in the bags may become strained or partly opened.

From observations made during lift-out tests, it appears that the difference between factory fresh and scuffed or damaged ballast bags may be quite substantial. No tests of this difference were made under this task order, but it would be relatively straightforward to do so.

Damping. In addition to the drainage of water ballast, a damping force also exists as part of the resistance to lift-out. Damping forces may be linear (e.g., wave radiation) or non-linear (e.g., viscous or non-linear free surface effects). However, the lift-out speeds required in the test are quite slow, on the order of 1 ft/sec for typical 20-man raft dimensions. Consequently, the contribution of damping forces to the lift-out force must be very small.

"Suction" or "Adhesion." Suction refers to the presence of a partially evacuated air space between the bottom of the raft floor and the water surface. "Adhesion" is a term which is potentially misleading, since it implies that there is some kind of bond between the water and the raft, which cannot be literally true. However, the term has been used to refer to the apparent sudden change in vertical force when a flat-bottomed hull emerges from otherwise smooth water. This is often interpreted as a transient force which results from forming a region of low pressure between the raft underbody and the water surface before air flows in to fill it. However, unless there is an air space, "breaking the vacuum" is not a particularly good explanation for lift-out force, even for a rigid body, and especially for a quite non-rigid body which is obviously capable of large local deflections under load.

A better model of the transient velocity-dependent forces during emergence is to consider the section forces during a slam or water impact. The resemblance between these phenomena becomes clearer when it is realized that both forces are essentially inertial in character. The first-order quantity which governs section forces at low relative velocity is the derivative of added mass with respect to section immersion. If this derivative is denoted by dA/dz, and the rate of change of immersion by dz/dt (the section's relative vertical velocity), then the section force becomes $(dA/dz)\ (dz/dt)^2$. For a rigid perfectly flat bottom encountering a perfectly flat surface of incompressible fluid, the derivative dA/dz becomes infinite at initial contact with flat water during immersion. Consequently, the section force with a non-zero immersion velocity also

becomes infinite. What is perhaps less obvious, in a flat-bottom emergence under the same idealized conditions, the derivative also becomes infinite at the final contact with the surface, with the same mathematical result.

In a real impact the section force is finite but large: air is present between the body and the surface, the real body is elastic, not infinitely rigid, and even the water is (if only slightly) compressible. In an emergence, the section force is reduced further by the fact that the surface cannot remain even approximately flat when the raft emerges, because the entrained water has inertia. Transient pressures and section forces are consequently not experienced equally in a slam and an extraction. However, the point remains that so-called "adhesion" cannot be understood as breaking an actual bond between the raft and the surface, but mostly as a transient inertial phenomenon, even for a body far more rigid than an inflatable life raft bottom.

"Suction" is mentioned here because of the use of the phrase "suction force" to describe a force which resists lift-out. In a lift-out test of certain types of rafts, especially reversible rafts, there can be an aerostatic force due to low pressure in the air space between the water surface and the raft floor which can remain several inches off the water. When a reversible raft is placed gently afloat, unloaded, the air pressure under the floor is slightly above atmospheric because the air is compressed slightly as the raft sinks to its equilibrium position. Assuming no change in temperature, when the raft is lifted out, the air pressure returns to atmospheric just as the raft bottom emerges. However, when a raft is loaded while afloat, the floor is brought closer to the water, both by deflection of the floor and sinkage of the buoyancy tubes, compressing the air in the space. If, while the raft is still loaded, this air space is allowed to communicate with atmosphere, say by a wave or other disturbance, then the pressure in this space will equilibrate with atmosphere, and subsequently it will drop below atmospheric when the raft is unloaded. The resulting "suction" force can be many times greater than the lift-out force measured on a raft which has remained unloaded. It may be this phenomenon which has resulted in the common misconception that rafts produce a force that can be described as "adhesion" to the surface.

Peak Force Criterion. In Reference 4, the required minimum acceptable peak lift-out force is stated as a polynomial in P, the number of persons for which the raft is to be approved. As a result, the required force is only indirectly related to the magnitude of the presumed windage or wave forces that might be experienced by the raft. For a non-circular raft, it should be anticipated that these forces would vary depending on whether the raft were lying broadside to wind and waves or "bow" to (for example, if stabilized in that orientation by an effective drogue). In any case, the use of a variable peak force requirement, depending explicitly on raft dimensions, rather than on rated capacity, would be more physically realistic.

Peak Force Criterion versus an Energy or Impulse Criterion. The lift-out force criterion of Reference 4 is stated solely as a required peak value of the force. It does not contain an energy or impulse-like requirement (that is, the integral of the force with respect to distance of action, or time). From the standpoint of over-all capsize resistance, it is suggested that a lift-out force record having a high peak, but one which acts only for a small range of hoist, or short duration, may actually represent less effectiveness against capsize than a force record with a smaller peak force but a larger range of angles. By analogy with ship stability requirements, the

integral of the lift-out force profile represents a dynamic stability criterion, while the maximum value per se is analogous to a required minimum righting arm. It is suggested that an improved criterion would include <u>both</u> a required peak force and a required integral over the lift angle.

<u>Bridle Geometry.</u> As a final comment on the a lift-out test methodology, the arrangement of the bridle can obviously have an effect on the result. The wording of the proposed rule states that the bridles can be attached either to existing fittings or fittings installed for the purpose, but does not specifically limit where these attachments must be located. It is clear that the bridle effectively applies a point or multi-point load that can lead to a rather arbitrary deformation of the raft during the test, which is not truly indicative of the distribution of either windage or hydrodynamic forces on the raft.

The proposed rule does specify that the force must be applied at the "outer edge of one of the main buoyancy chambers." Further, for a raft which is not essentially circular in plan, it must be tested with lift forces applied in two locations: "once at one end of the major axis of the waterplane, and once at one end of the minor axis of the waterplane." However, these terms, taken strictly, seem to imply a single point lift which may not be practical. On the other hand, the tester cannot have the freedom to bridle anywhere other than at the "end" or "side" of the raft, without defeating the intent of the test. It is suggested that a more tightly specified procedure should include specific designations of permissible deviations for attachment points inboard from the "end" or "side" of the raft, as a percentage of raft length or breadth, respectively.

<u>Summary Comments.</u> The lift-out test force test clearly measures <u>something</u> related to raft capsize, in fact several things at once, but not independently. An experimenter who was blind to the raft geometry, and only saw the lift-out force results, would be able to identify which rafts were heavily ballasted and which were not. However, this is primarily because the center of gravity of the raft is raised by the applied lift-out force. In effect, the experiment weighs the raft and its ballast, which drains in a time and angle-dependent way. This is unlike the case of a pure inclining experiment, in which the raft remains at constant weight or displacement.

The lift-out force is therefore to a great extent a measure of weight, but also heavily influenced by the flexure of the raft in transmitting forces to the lifting point, and the partial drainage of ballast during the lift-out. The force does <u>not</u> provide a direct indication of range of stability, energy to capsize, energy to re-right, or inertia. As will be pointed out below, all of these are important, and for some capsize mechanisms may be more important than the quantities that combine to produce the lift-out force result.

3.2.5. Asymmetric Loading

Heeling moments due to asymmetric loads, particularly during initial occupant entry, when the weight of the entering personnel may be applied substantially outboard of the buoyancy rings, can be a significant source of inclination for unballasted rafts. Significant heeling moments can also occur if all occupants are closely packed toward one side of the raft. With normal precautions, this type of extreme asymmetric loading would be avoided, however, it could result from unrestrained and involuntary shifting of the raft's occupants, such as in a near capsize.

For heavily ballasted rafts, the heel angle during initial boarding of the first occupant is quite small, and it is not possible to capsize such a raft in this way. The maximum reasonable heeling moment with the occupants closely packed to one side of the raft can be compared against static stability. Typically, in the worst case (which may or may not be at the full rated passenger load), this can produce inclinations up to 20 or 25 deg. Capsizing due to this source alone is therefore not a fundamental problem for heavily ballasted rafts.

However, when applied in addition to other heeling moments, which may occur when occupants become asymmetrically distributed as a result of a large attitude change and the raft is then subjected to another wave or wind load before the occupants can regain their positions, it is judged that the situation may become marginal even in a ballasted raft.

Requirements for occupant restraints, including belts, have been considered (Reference 4). At present, suitably placed handholds are considered sufficient to avoid unrestrained movements of the live load. There is ample evidence from rigid survival capsule experience that more positive restraints, such as belts or harnesses, would be advantageous from the standpoint of avoiding injury during large attitude excursions or impacts. It would also be a benefit in capsize resistance. By ensuring more positive location of the occupants, restraints would tend to limit an additional source of heeling moment and would also ensure that the occupants contribute as much as possible to the inertia of the raft.

However, some opinions have been expressed that belts might be psychologically counterproductive for life raft occupants. In unballasted rafts, which are more subject to capsize, the ability of unrestrained occupants to "scramble for the high side" may be considered as a psychological advantage, if not a physical damper of heel angle.

3.2.6. Captured Air under the Raft Body and its Effect on Stability

Comments have been made by some raft manufacturers (in Reference 11, for example) regarding the possibility of capturing air under the raft body in rafts with a toroidal ballast bag, and producing a destabilizing effect. Captured air, if unable to escape, would cause the upright raft to float higher in the water. It would not, however, produce a net free-surface correction to the inertia of the raft's waterplane, unless the initial waterplane inertia had been calculated to include the area inside the inner boundaries of the toroid. Consequently, the stability of a raft with a toroidal ballast bag should exclude this inner area from a waterplane inertia calculation.

For typical toroid proportions, the inside diameter on a small raft is approximately 70 percent of the outer diameter over the buoyancy rings. Since the area moment of inertia of a circle about its diameter is proportional to D^4, however, the loss of waterplane inertia by excluding the inner area is limited to about one-fourth of the total. Once the raft is shown to possess adequate initial stability using the reduced waterplane inertia, then captured air under the raft body does not represent a further destabilizing influence, statically.

In any case, if the volume under the raft body is permitted to communicate with the atmosphere, such as by openings in the top of the toroidal ballast bag, then the issue of captured air is moot.

3.2.7. Raft Responses on the Crest of a Sharp-Crested Wave

In waves of modest amplitude, the behavior of floating bodies is usefully well-represented by linear seakeeping theory, as presented for example in Reference 28. Linear theory is based on computing the inertia (including hydrodynamic added mass), damping (which in pure linear theory does not include viscous forces, and restoring forces (i.e., stability) of a floating body, and the exciting forces acting on the body due to a wave. These forces are then used to solve for the response of a linear spring-mass-damper system, which represents the body. In general, the hydrodynamic forces (added mass, damping, and exciting force) are frequency dependent.

The limitations of linear theory arise primarily from: (1) The fact that inertia, damping, stiffness, and excitation are computed entirely from the characteristics of the body floating at its mean position, and (2) The exclusion of forces that are non-linear, especially damping due to viscous forces, which is important primarily in roll (for ships), but in both pitch and roll for rafts (due to low length to beam ratio, flat body shape with small radii at bilges, small size and consequently low Reynolds numbers).

As a result of these limitations, linear theory in general fails to give good prediction in roll, (without empirical corrections) even at moderate angles, and is of little use in the prediction of capsize behavior. In ships, large amplitude rolling near resonance is often observed, and under some extreme conditions can place a body in danger of capsize. However, as pointed out above, synchronous roll or pitch is not of particular interest in life raft design, because of the short natural period of typical rafts.

As Froude pointed out as early as 1861 (Reference 29), the lateral and vertical accelerations experienced by a small body in waves (that is, a body of small dimensions with respect to wavelength and consequently surface radius of curvature) are such that a pendulum supported in the body tends to remain perpendicular to the local water surface. This observation leads directly to the statement that the "apparent direction of gravity" is directly toward the local wave surface. This observation remains valid even for waves of large steepness, including breaking waves, provided that the bodies dimensions are small with respect to the surface radius of curvature.

However, Froude's observation does not lead to any ability to compute the capsizing forces exerted on the body by local breakdown of the wave surface, including forces in spilling or plunging breakers (forces exerted by a spilling shear layer on the surface of a steep wave, or by a plunging jet of water from a breaking crest).

In deep water, the assumption of two-dimensional, inviscid flow (see, for example, References 21, 22, and 30) leads to a limiting value for the surface slope and height to length ratio of a periodic non-breaking wave. The limiting wave is shown to have a cusp at the crest, with an included angle of 120 degrees, and a height to length ratio of approximately 1/7. This limiting case reflects the situation when the velocity of flow at the crest is just equal to the phase velocity of the wave. If the flow velocity exceeds this, the water near the wave crest cannot remain coherent with the wave, and over time it must either spill down the face of the wave or

form an emergent jet (a plunging breaker). Because of the presence of a cusp, the limiting non-breaking wave in deep water can be referred to as a "sharp-crested" wave.

On the crest of a sharp-crested wave, a floating body experiences a rapid change in hydrodynamic force and moment. The change in force and moment occurs abruptly because the crest's velocity is the phase velocity of the wave, while the raft (especially if heavily ballasted) resists being accelerated to this speed, due to its high drag and its inertia. Consequently, the raft's velocity may be only a small fraction of phase velocity, and the time for the raft to traverse the wave crest is short. The general response, not considering windage, is an abrupt change in inclination of the raft toward the direction from which the waves are coming

On a wave which has a crest included angle near the limiting value of 120 degrees, the resulting change in attitude of a raft of small dimensions with respect to wavelength can become quite severe. Normally, the craft recovers its restoring moment after reentry into the back of the wave. The abrupt drop and roll to waveward from the crest of a sharp-crested wave tend to be in the opposite senses from wind forces and moments near the crest, if it is assumed that the wind and wave propagation directions are relatively close together.

By contrast, it is speculated that a light, unballasted raft, especially one without an effective drogue, is capable of accelerating on the face of the wave to a speed much closer to the wave's phase velocity. Consequently, the passage of the raft over the crest of the wave occupies a longer period of time, during which windage forces can supply the impulse required for capsize. This difference in impulse, in addition to the greater angular inertia of a ballasted raft, tends to explain why wind forces, even on the crest of a sharp wave, generally fail to cause capsize of a heavily loaded or water-ballasted raft in conditions where light rafts do capsize.

Unfortunately, such an idealized condition, with wind and waves in the same direction, may not be present under all conditions. In short-crested or confused seas, for example, there is no reason to expect wind and wave-induced moments to act in the same plane at all times. In the presence of short-crested waves, the loss of righting arm that occurs during a nearly free fall onto the back of the wave may be accompanied by rolling moments and velocities in planes other than the plane normal to the crest of the local wave.

In very short-crested or confused seas, even non-breaking, it is difficult to see how a drogue can be fully effective in resisting roll excursions due to the cross component of wind or wave forces. Under these conditions, the primary ingredients of capsize resistance are small windage moment, large range of stability, large righting energy, and high inertia. In any case, it is judged that lift-out force, alone, is not a real measure of capsize resistance on a sharp crest.

3.2.8. Forces and Moments due to Breaking Waves

Two primary types of breaking waves are recognized, both in surf and in deep water. They are usually classified as "spilling" and "plunging" breakers. The physical characteristic common to both types is that water particles on the free surface near the crest obtain a horizontal velocity component exceeding the phase velocity of the wave. Consequently, there is a mass of

water which cannot remain coherent with the wave, but accelerates away in advance of the wave's over-all propagation.

Whether a wave breaks as a spilling or plunging breaker is determined to a great extent by the rate at which the surface particles acquire their excess velocity. A rapid increase in excess velocity results in a plunging breaker, with the crest assuming the form of an emerging "jet" above the face of the wave. This develops into the characteristic curl, often enclosing a volume of air underneath as it falls back toward the surface under the effect of gravity, and abruptly becomes re-entrant to the surface.

A more gradual change in excess velocity typically causes the crest to become locally unstable but without forming a jet. In this case, Longuet-Higgins suggested (see Reference 15) that the mass flow reorganizes itself as an accelerating "turbulent gravity current" flowing down the face of the wave. At small scale, this flow is a "whitecap." At large scale, it is a spilling breaker.

The flow in a spilling breaker remains distinct from the underlying water mass for a considerable time, firstly because it can only entrain further momentum by turbulent mixing, which is a relatively weak transport, and because it also entraps air in the form of bubbles (rather than as a large single volume), thereby supporting a density as well as a velocity gradient. The entrainment of mass increases the volume of the spilling layer, and the entrainment of momentum produces a drag which gradually reduces the acceleration of the layer due to gravity.

In shoaling water, the tendency of waves to break is significantly affected by the change in phase velocity, which decreases as the water depth becomes shallower. For this reason, the type of breaker in surf is influenced by the bottom gradient, a relatively strong gradient producing plunging surf, while a shallower gradient produces spilling.

In deep water, the rate at which excess particle velocity occurs near a crest depends on the specific superposition of waves leading to a slope beyond the breaking limit, and intuitively there should be a mix of plunging and spilling breakers observed. In typical observations, more spilling breakers are usually observed, although this may be due to the relatively short life of an organized jet before it re-enters. Once a horizontal jet forms, it must fall at approximately a 1 g acceleration, and it must therefore become re-entrant within a time on the order of $t = (2h/g)^{1/2}$, where h is the height of the wave. By contrast, if the wave spills, the spilling layer can start from a small disturbance and propagate down the face of the wave. A constant "terminal" downslope velocity is reached when the drag caused by entrainment balances the component of gravity along the slope. This is very much like an avalanche, and may persist for several seconds, a sizable fraction of a wave period.

3.2.8.1. Capsizing in a Spilling Breaker

In terms of potential effects on a raft, a spilling breaker is also somewhat like an avalanche. This is clearly difficult to generalize, because the effects on a particular raft, even when the breaking wave's form is exactly repeatable, will vary depending on where the raft is on the wave when impact occurs. As an example, however, the downslope shear velocity just below

the crest, where the slope may be near its maximum value of 30 deg, is about 12 percent of phase velocity (with a typical 8 percent density difference between the breaker and "solid" water), according to Reference 15. If the breaker is a large wave, the depth of the spilling layer can reach the order of raft dimensions, although this may not happen until further down the face, where the slope is reduced, the layer is thickened, and the shear velocity is consequently less.

In any case, the impact of a spilling breaker with a raft body and canopy can easily represent an overturning moment as large as that of hurricane-force winds. Suppose, we assume that the same drag and moment coefficients are taken for both windage and the forces due to the flow in the spilling layer. (This is clearly a major simplification, but will serve to illustrate the relative order of magnitude of the problem.) The density ratio between air and 8 percent aerated water is 1/770. Consequently, as an approximation only, a capsize moment equivalent to 63 knot wind would require only about a 4 ft/sec spilling breaker flow velocity averaged on the "above water" part of the raft.

If the spilling flow is taken as assumed above, a typical wave phase velocity for the breaking wave only needs to be about 33 ft/sec. This corresponds to a breaking component of about 6 sec period, or 200 ft wavelength. The breaking limit steepness would be reached at a height of about 28 ft at this wavelength. This is about the height of one wave in 1000 (over the entire spectrum) near the middle of seastate 6 (15 ft significant wave height).

Without further data on actual capsize observations in breaking waves, it is not possible to state that a 63 knot wind force criterion is any less safe than a 4 ft/sec spilling wave shear velocity criterion. It must be remembered that a spilling wave force cannot be sustained indefinitely: first because the current eventually runs out onto the flatter portion of the wave face and decays, and second because the raft will tend to rise through the spilling layer.

On the other hand, it is hypothesized that as the spilling wave moment inclines the raft, its exposure to the velocity difference in the spilling layer may increase in somewhat the same way as the emergence of the upwind edge does in a windage capsize. Since the drag on the spilling layer is imposed by entrainment from the wave surface underneath, it is reasonable to suppose that the velocity gradient in the spilling layer is at least as steep as in steady wind flow over a water surface, and possibly even steeper. Consequently, the increase in capsizing moment with inclination may be even greater in a spilling breaker than in pure windage.

However, in spite of these uncertainties, which the literature does not resolve, what the comparison does make clear is that a spilling wave impact need not occur under hurricane conditions in order to represent an impulsive capsize force of considerable magnitude, at least of the same order as the assumed 63-knot windage. It may be noted that the typical sustained wind speed for mid-seastate 6 is less than 40 knots, not hurricane force.

3.2.8.2. Capsizing in a Plunging Breaker

As mentioned above, in deep water, spilling breakers are more frequently observed than plunging breakers, although the actual proportions are not known. A great deal of the literature on capsizing of sailing craft, however, is concerned with capsizing in a plunging breaker. This is

considered to result from certain aspects of yachting experience which would tend to skew the results from what life rafts would experience under similar conditions of wave height, namely:

(1) Waves in shoaling water may be involved to a greater extent in coastal racing and cruising. This would tend to produce a larger proportion of plunging wave encounters due to bottom gradient.

(2) In following seas, yachts are capable of picking up a great deal of speed as they are overtaken by steep waves, even when running under storm sails or bare poles. For this reason, they may not tend to encounter breaking waves at the same phase as a heavily ballasted and extremely high-drag raft.

(3) Broaching may be involved in some of the yacht capsize incidents. This adds the even further complicating elements of forward speed and maneuvering (rudder) forces to those imposed by wind and waves.

(4) Yacht capsizing, in some cases, may involve nearly simultaneous dismasting, with rapid (and unfavorable) changes of the over-all moment of inertia of the craft.

The literature of yacht capsize therefore tends to highlight the hazards of plunging breakers. In a plunging breaker "strike," it is largely the emergent jet which produces the velocity gradient and moment to overturn the body. Peak jet velocities may be as much as 2 to 2.5 times the phase velocity of the wave. Although the jet may be confined to a relatively smaller area than a spilling front, depending on the phase at which the impact occurs, it may also tend to strike high on the craft's freeboard.

Forces on a body due to a plunging wave jet are extremely shape dependent and difficult to predict. They are also highly unsteady and of short duration. Further, with the jet impact most likely to occur on an inflatable raft's canopy, it is difficult to imagine that the response of the raft under a plunging wave strike would really resemble that of a rigid hulled body. In spite of the difficulties of computation, it is certain that capsize in a plunging wave impact results from an impulsive load of extremely high magnitude, intense enough to cause structural damage to hulls. For typical wave scales leading to capsize, initial stability is simply overmatched. Survivability is most likely to be conferred through local flexibility of the structure, global inertia of the raft and its ballast, and a large range of stability (preferably including self-righting).

In conclusion, it should be stated that in all documented tests of heavily ballasted life rafts, model and full-scale, the precondition for near capsizing was the existence of breaking waves, and especially of plunging breakers. Although model tests, such as those documented in Reference 6, may not quite accurately represent the flow velocities in a breaker in deep water, they clearly illustrate that capsize can occur in breaking waves without lift-out as a precondition.

3.2.9. Overturning on the Interior Surface of a Plunging Breaker

In a very large plunging breaker, say with a height of several times raft diameter, an additional capsizing mechanism exists, which does not result from the impact of the emergent jet.

In such a case, the emergent jet may be entirely above the raft, and no water impact would occur until the jet re-enters the water and the breaker collapses. However, the raft could ride completely around the interior surface and end up inverted, or past inverted, without actually experiencing a large "inclination" from its local apparent vertical.

There is absolutely nothing that can be done about such a large breaking wave through stability, except in the sense that self-righting capabilities are desirable after the fact. However, it could also be useful to investigate design elements that would enhance survival against the personnel safety consequences of impact.

There is in fact a double impact to consider, probably occurring in rapid succession. The raft encounters the water surface downslope from the breaking crest. It is also hit on the opposite side by the collapsing breaker. Essentially, these impacts can both occur with a velocity corresponding to free fall from a height fairly close to that of the wave, so that the velocities may be high.

Further, the attitude of the raft during impact may be at a large inclination to the surface, possibly even inverted. This indicates that the primary survivability issue would be occupant protection against impact injuries, including being struck by equipment or other occupants, and crushing injuries. It is questionable whether an inflatable raft can provide sufficient stiffness to give protection against crushing injuries in severe impacts. However, occupant restraints and protective gear, especially headgear, may be considered.

Since large loads and deflections may be involved in such high energy impacts, the strength of the raft (buoyancy rings, ballast bags, and canopy) will also be important in survival, as will the raft's righting capabilities (including self-righting).

Finally, there has been some controversy regarding the most favorable location for heavy water ballast appendages, and whether ballast itself can present an additional potential source of injuries in a capsize. This is addressed in the following section.

3.3. Effects of Water Ballast During and After Capsize

Concerns about the safety of heavily ballasted rafts have arisen from the fact that the weight and inertia of heavy ballast would result in generally larger loads and deflections of the raft during a capsize. In particular, there has been considerable argument (in Reference 11, for example) that a heavily ballasted appendage in a highly deformable structure (such as an inflatable raft), could intrude into the passenger volume and actually increase the risk of crushing injuries or entrapment in a raft which may stabilize inverted.

There can be no question that a heavy raft must be materially stronger, in order to support the weight and inertial loads from the ballast bags. It is not very surprising that in early testing of ballasted rafts (References 10, 31, and 32), the tearing away of ballast appendages was observed in several cases. The loads were not predicted accurately (and in fact could not have been

predicted accurately by conventional seakeeping analysis). Therefore, trial and error were to be expected.

However, with regard to the presumed potential for increased risk of crush injuries because of certain ballast arrangements (in particular, hemispherical) it must be concluded that the examples usually shown are artificial. The usual example (as found in Reference 11) is to portray two heavily ballasted rafts, one with a toroidal distribution of ballast (or a series of bags around the perimeter), the other with a hemispherical ballast bag, subjected to what can best be described as an inverted drop test. The portion of the sea surface that is shown is an essentially flat plane, onto which the rafts impact, upside down. The part of the fluid domain responsible for putting the raft into this attitude, however, is usually not represented.

In the idealized case of an inverted drop test onto a water surface, it could be argued that the hemispherical ballast would have to deflect the non-rigid floor into the passenger volume before it could transfer the load to the buoyancy rings (recalling that bending stiffness may be nil) by membrane tension in the floor. On the other hand, a toroidal ring of ballast, positioned directly over the ballast rings, would be able to load the rings directly, without sagging the floor into the passenger compartment.

However, in the presence of a breaking wave which has just overturned the raft, it must be remembered that the ballast is not the only mass of water which must be decelerated and supported by the raft upon impact. In fact, the mass of water which must be decelerated is approximately the same whether it is in the wave or in the bag. This is not to say that the dynamic response is identical between the two cases. Nonetheless, the point is that the two situations are not truly as different as the over-simplified picture indicates, once the presence of the momentum of water in the wave is recognized.

Even more to the point, however, is the fact that water impacts -- whether from impingement of a breaking wave jet, or from rapid immersion in a spilling breaker, or from free fall into the trough -- can occur with the raft in a variety of orientations, of which a pure upside-down fall onto a flat water surface is not necessarily most likely. In some orientations, the hemispherical ballast can be viewed as an interposed mass between the impulsive load and the occupants of the raft, rather than as an additional load. Further, the gross acceleration of the raft due to impact is reduced by the mere presence of the additional ballast mass. For these reasons, it is concluded that the supposed hazard of raft occupants being crushed by their own ballast is not physically realistic, and that no appreciable difference in impact safety accrues from either ballast configuration.

With regard to entrapment in a hemispherical-ballasted raft which becomes stabilized inverted, the question is basically two-fold. First, assuming that the raft is stable inverted, or that it is artificially held inverted, is the sag of the passenger compartment floor under the static load of ballast large enough to cause entrapment? Second, how stable is the inverted raft? These two questions are coupled, in the sense that the sag of the boundary between the ballast and the passenger space changes the location of the ballast water, and consequently the stability when inverted.

Without performing detailed calculations on a particular raft geometry, the ballast bag of a hemispherical ballast raft with typical buoyancy ring proportions would be immersed to about 40 percent of its radius if it were held in the inverted position, so the net static head acting on the boundary is only approximately 60 percent of the ballast bag radius. This is about a 3 ft static head for a 10 ft diameter raft, or only about 1.3 psi, putting a strip loading of 110 lb on a one-inch wide strip across the diameter of a 7 ft passenger compartment. The sag of the boundary would depend on the construction of the floor, the membrane characteristics of the floor, and the flexural characteristics of the buoyancy ring to which it is attached. It should not be expected that the sag would be very large under this load, certainly not more than a few inches, a fact which can be judged by placing a similar load on the raft floor upside down in air.

It appears that the example raft would be slightly unstable inverted, with no sag of the boundary, neglecting buoyancy contributed by the canopy or air entrapped in the passenger space, but also neglecting the weight of the occupants. That is, such a raft is statically self-righting. With a few inches of boundary sag, the raft could become slightly stable inverted.

It should be pointed out that even a toroidal ballast compartment would be capable of retaining some depth of water on the floor of an inverted raft, until it could drain off. In this sense, an interrupted ballast bag arrangement would be preferable because it would shed the load faster. However, this is a mixed blessing, because the top weight and free surface are both destabilizing influences on the inverted raft, and consequently assist in self-righting.

In any case, it is judged that crushing or entrapment of occupants due to the sag of the floor in an inverted raft is unlikely with either ballast configuration, although a difference in self-righting capability certainly may exist.

3.4. Self-Righting

In principle, self-righting is a desirable feature in any raft, and this becomes increasingly important for larger multi-person rafts. However, for a broad, shallow-draft form which is typical of many life rafts, static self-righting capabilities are extremely difficult to obtain. Flat rafts, as well as those with circumferential ballast bags of usual proportions, are typically statically stable inverted.

An alternative ballast arrangement, perhaps best represented by the Givens design, which has a very large spheroidal ballast bag, may achieve a righting arm curve which is statically self-righting (that is, with the inverted equilibrium unstable), or nearly so, provided that the ballast bag remains intact and retains a sufficient part of its contents for a sufficient period after inversion, and does not deform excessively into the passenger compartment. Claims of self-righting capability have been made for the Givens design.

The effect of an erected canopy on stability at large angles of inclination is difficult to estimate quantitatively and, it is judged, would not be easy to measure repeatably by experiment. Typically, the stability of a canopied raft at large inclination could not be truly static in any case,

because the canopy is highly non-rigid (significantly less rigid than the buoyancy rings, and generally cannot be made watertight. Once large deformations and flooding of the passenger compartment begin, the restoring moments must become critically time-dependent.

Current and proposed USCG rules do not require a raft to be self-righting, but invoke SOLAS 74/83 requirements. These specify only that a raft must be capable of being righted by one person in the event that it is inflated (unloaded, of course) in an inverted attitude. This is important, too, but it does not specifically address self-righting after a capsize in heavy seas.

In the 1994 NPRM, USCG takes the position that self-righting after a capsize is an overly stringent requirement because a raft which meets the other ballast system requirements, including lift-out force criteria, is unlikely to capsize. Further, recovery from a capsize in heavy seas does not require a curve of righting arms that shows static self-righting.

In characterizing the ability of a craft to recover from a capsize in heavy seas, even in plunging breakers, the term "self-righting" has been used other than in the static sense. In a dynamic seaway, a broader definition of "self-recovering" (as distinct from self-righting) can be discussed in terms of the ratio of energies, E_c/E_r, where E_c is the "capsize energy," the integral of righting arm from statically upright to the point of capsize (the point of vanishing righting arm), and E_r is the "re-righting energy," the integral of the righting arm curve from statically stable inverted to the point of recovery, as shown in Figure 1.

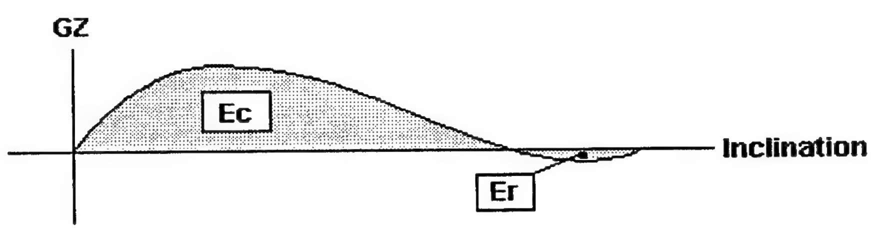

Figure 1. Righting Arm vs Roll Angle.

A "self-recovering" criterion, for example, can be established in the form $E_c/E_r > C$, where C is a criterion value to be specified. This form of criterion has been invoked in recent specifications for U.S. Marine Corps amphibious vehicles (Reference 33). The physical justification for this type of criterion is that in wave conditions extreme enough to capsize the vehicle, there is a strong likelihood that a subsequent wave, within a relatively short amount of time, will arrive with sufficient energy to re-right it. An energy ratio measure, or some variant of it, is clearly less stringent than static self-righting, that is, righting arm vanishing at 180 deg inclination and an unstable equilibrium at 180 deg.

It would be interesting to compare the energy ratios of existing ballasted rafts, by computation, using the hydrostatics of the "rigid" form as a first approximation, and for cases including or neglecting canopies. Subsequently, these estimates could possibly be compared with experimental results, limited to calm water, in which ballast appendages are free to deform and

drain naturally. However, it is judged that physical testing to validate these estimates by tests of full-scale inflatable rafts would be difficult, because of large deformations and flooding details.

Righting energy is considered an important element in yacht capsize resistance, for example, as noted in Reference 7. It is judged to be similarly important in raft capsize. Unfortunately, as stated above, the prediction or experimental measurement of righting arm as a function of inclination to large angles, is more difficult for an inflatable raft than for a yacht hull. Because of the effects of deformation and flooding, furthermore, experimental righting energy could be rate-dependent as well.

It is not recommended that a self-recovery energy ratio criterion be imposed by rule at this time. However, energy ratio information might be useful as a guide for raft development independent of rule-making. In any case, it is strongly suggested that capsize-resistance criteria which do not include some measure of the integral of force or moment, that is, an energy measure of some kind, cannot correctly represent capsize behavior in general.

3.5. Effects of a Drogue on Capsize

The use of a drogue to provide a counter-capsizing moment or force must be distinguished from its undeniable advantages in reducing the drift speed of an unballasted or lightly ballasted raft. A drogue also acts to reduce the horizontal acceleration of the raft on the face of a wave, which in turn reduces its time of exposure to windage or hydrodynamic (breaking wave) forces near the crest. Much of the work performed on drogues as a means of alleviating capsize hazards (such as References 16 and 25) has concentrated on yacht capsize prevention, but there are some sources which specifically address rafts (References 31 and 32). For this reason, some of the conclusions regarding the effectiveness of drogues must be evaluated with due regard for the differences in capsizing behavior between yachts and life rafts.

A drogue may act to resist capsize (or yacht pitchpoling) in several ways:

1. By producing a moment against wave or wind inclination to leeward, which increases as the inclination increases, and may delay or prevent lift-out.

2. By augmenting the raft's damping or inertia.

3. By providing a drag force which restrains the craft from accelerating horizontally on a wave, in advance of the crest, thereby reducing the <u>duration</u> of the interaction with a breaking or sharp wave crest.

4. By resisting yaw, in effect keeping a raft "head" to sea. (This effect has an obvious interpretation for rectangular rafts, but it may be meaningful even for circular rafts, with reference to the distribution of occupants, and the consequent location of the center of gravity.)

All of these effects may be important in extreme conditions. However, all of them depend on the drogue line providing the resisting force. Consequently, as noted in References 31 and 32, drogue forces depend on the phase of motion not only of the raft, but of the drogue as well. Clearly, they also depend on the drogue remaining properly streamed, unentangled in its own bridle, and relatively undamaged, so that it remains capable of exerting a useful drag force.

The main difference between the cases of a yacht and a life raft is forward speed, particularly the ratio between average forward speed and the oscillatory velocity due to a wave. In the case of a heavily ballasted raft, the body's speed through the water is considerably less than that of a yacht. Consequently, a drogue line which is constantly taut for a low drag, high windage yacht may experience considerably more frequent and longer intervals of slack, in a given seaway, for a raft. For a conventional drogue, much like a parachute, experience has shown (as pointed out in References 25, 31, and 32) that when the load is removed the drogue may collapse, or tumble into its own bridle, losing its effectiveness.

The effectiveness of the drogue as a drag asset, changing the raft's speed through the water, may be somewhat less for a raft than for a yacht. For a heavily ballasted raft, the drag of the underwater body is already so high that a conventionally sized drogue would have relatively less effect. Nevertheless, for a lightly ballasted raft, and especially one that has not yet been boarded by personnel, the drogue may be critical to both drift rate and capsize resistance, as confirmed again during the sea tests described below.

An effective drogue acts mainly to reduce the amount of time during which the raft can be acted on by a breaking or sharp wave crest, and by holding the raft bow to the seas. In terms of direct resistance to wave or wind generated overturning moments, even when the pendant tension is high the drogue does not generate large moments until the raft reaches relatively large pitch angles.

The 1994 NPRM concludes that for a heavily ballasted raft a drogue is not particularly useful. This opinion is rather difficult to reconcile with the results of References 31 and 32. These references conclude that an effective drogue contributes considerably to capsize-resistance quantities which are <u>not</u> measured in a lift-out force test. There is a considerable body of opinion that a drogue must be considered as an essential adjunct to capsize resistance.

On the other hand, arguments for <u>not</u> explicitly including the effects of a drogue, while heuristic, have some basis. For example, it has been pointed out that waves and wind may be acting from considerably different directions at a particular instant. This is especially clear in a short-crested or confused sea, which would not be unusual under storm conditions. It is argued that this spread in angle tends to reduce the effectiveness of a drogue because it is not able to contribute full capsize resistance except about an axis perpendicular to the drogue line. For this reason, at the instant that an impulsive wave load is encountered, the drogue line may not be positioned to give its full resisting effect, even though the line is taut and the drogue is fully spread.

It has also been pointed out that a drogue, deployed on a long enough scope and weighted to stream well below the surface, which is desirable from the standpoint of fouling due to its own motions, will also be subject to different second-order wave (steady drift) velocities than the raft body. Consequently, it is not clear that a weighted drogue would always stream directly upwind, and that it might wander considerably in response to wave forces under certain conditions.

Arguments emphasizing the importance of the drogue, such as References 31 and 32, often state that ballast bags produce no effect on capsize resistance until they are lifted out of the water. That is an over-generalization which ignores the influence of inertia: water ballast bags do not contribute to restoring moments at small inclinations, but they contribute a significant amount of inertia. Further, because of the wide, flat geometry of most life rafts, the angle of inclination at which ballast bags do begin to contribute to righting moment is actually rather small. Even in References 31 and 32, the drogue, though considered an essential part of a capsize-resistance system, is not considered to be a substitute for water ballast. Ballast bag sizes have been progressively increased as a result of sea tests, as described in References 31 and 32.

A final issue relates to the design of drogues and pendants. By comparison with a yacht, more frequent slackening of the drogue line should be expected for a heavily ballasted and inherently high-drag raft. For this reason, it is concluded that a drogue design which improves stability and reduces the likelihood of fouling in its own bridle due to the reduction of tension, is quite important. Further, improved drogue and pendant designs can reduce the magnitude of the peak pendant loads. Such drogue designs are described in References 25, 31 and 32. They include a longer drogue, with a smaller ratio of diameter to length, open end or permeable fabric at the end, tandem drogues, and deeper submergence obtained by the use of a longer scope and a messenger-weighted drogue line to ensure that the drogue remains well below the surface.

Based on indications in References 31 and 32, a pendant length corresponding to about a one-half wavelength separation between raft and drogue would be particularly susceptible to slackening, tumbling, and snatching, due to the 180 degree phase difference between wave amplitude and orbital velocity. However, practical drogue pendants, even when lengthened for deeper submergence and reduced snatch loads, are invariably far shorter than half the length of the modal wave in open-ocean storm conditions.

3.6. A Capsize Performance Measure for Life Rafts

At present, the proposed lift-out force test effectively stands as a criterion for capsize resistance for life rafts. However, as noted in the previous sections, maximum lift-out force alone is not considered to be a wholly satisfactory measure of the physical quantities that are believed to affect capsize resistance and recovery. In principle, if an adequate descriptive measure for capsize behavior did exist, it should be possible to show correlation of that measure with observed results in sea testing, with behavior in extreme conditions as reported by actual raft users, and with casualty data in general.

To be useful in this way, the measure would have to be based on physical quantities which can be adequately estimated by calculation, or at worst, measurable using relatively inexpensive test procedures. As a goal, required tests should not need more sophisticated equipment or measurement procedures than the current lift-out test.

Zseleczky (Reference 26), citing earlier work by Blume, Reference 27, noted a proposed criterion (or index) for capsize performance. This was given in the following dimensionless form:

$$P = (\pi\, GM \;\; F\, L\, D\;\, \zeta^2\,) / (\, E_c\, R^2\, V)\,, \qquad \text{[Eq 1]}$$

where P is said to be an index of increasing probability of capsize. GM is the metacentric height (static), F, L, and D are measures of the body's freeboard, length, and depth, respectively, ζ is the wave height, E_c is the area under the righting arm curve from upright to the point of capsize, R is the roll gyradius, and V is the displacement volume.

It is interesting that the metacentric height appears in the numerator of the expression, as the initial stability might be thought to confer an advantage against capsize rather than contributing to its likelihood. However, the meaning of this factor can be understood roughly as non-dimensionalizing the righting energy into a pure angular measure. It is also noteworthy that the range of stability does not appear explicitly, nor does the ratio of capsizing and re-righting energies.

Of the remaining factors, the product F L can be understood as a measure of exposed area above the waterline (whether this be taken as a windage or breaking wave exposure), while D can be understood as a measure of heeling lever arm. The product R^2 V is equivalent to roll moment of inertia divided by the mass density of water.

Consequently, leaving out constants and inverting (to produce a measure of capsize resistance rather than probability), the expression becomes:

$$N = (\alpha \;\; I_r\,) / (A \;\; H \;\; \zeta^2)\,, \qquad \text{[Eq 2]}$$

where α is the non-dimensional capsizing energy (E_c/GM), I_r is the roll moment of inertia, A is a "windage or wave-strike exposure area," and H is the lever arm giving a force a capsizing moment. The most appropriate values of A and H are not clear, nor necessarily unique, for all capsize mechanisms. The wave height is retained for generality, to provide the ability to tailor a numeral requirement for assumed ocean versus coastal conditions, for example.

Recognizing that raft capsize by definition implies inclination to large angles, and that capsize forces do not unload as the cosine squared of the inclination, it is not obvious that A should be the customary windage profile area as used in ship intact stability. Similarly, it cannot be obvious that H should be the customary lever from the centroid of the windage profile (or sail forces) to the half-draft or centroid of lateral plane (or hull and keel side forces), as in yacht stability.

However, if the exposure area A is taken, in the absence of a better insight, as the windage area, and the lever H from the centroid of A to the raft's center of gravity, as befits a problem dominated by inertia, then the quantities are at least defined. The immediate problem then is how to calculate, or measure, the quantities α and I_r.

If the raft and its ballast content were considered as a rigid body, as in a ship stability or seakeeping problem, then calculations would be trivial. The problem is very much complicated, however, by large deflections of the raft body and ballast bags at high inclination, by drainage of ballast, and perhaps equally importantly, by possible interior flows in a large unbaffled ballast volume. The lift-out test does not measure either α or I_r. Therefore, at present, presuming that these quantities cannot be adequately assessed by calculations using simplifying assumptions, such as rigid body and zero loss of ballast during capsize, it is considered doubtful that an accurate capsize resistance measure can be formulated based on simple calm-water tests.

4. OBSERVATIONS OF RAFT ACCEPTANCE TESTS

Life raft inflation, one-man righting, and canopy erection tests for the prototype HC-130 20-man SAR raft were witnessed at SWITLIK Parachute Company, Trenton, N.J., 4-5 February 1997.

An inflation test of the prototype raft was conducted at a local swimming pool. The raft was packed in its case, which was stowed inside a packing fixture configured to simulate the HC-130 wing stowage compartment. When the inflation cables were pulled, the raft inflated and emerged from its case to sit on the edge of the pool. The inflation sequence (main buoyancy tubes only, not canopy arches, which were furled and secured) took less than 10 seconds.

The raft was capsized with its canopy and supporting arches still furled. It was successfully righted by one man, using the righting line attached to the raft bottom, as required by SOLAS Chapter III, Regulation 39, Inflatable Liferafts. This test simulates the case of a raft which has deployed inverted, in relatively calm conditions, and is not intended to represent behavior of the raft in heavy seas.

The canopy was erected, with the arches being inflated by mouth, using the installed inflation fittings. Arch inflation took less than 1 minute each, and the total canopy erection took less than 5 minutes. (At a later date, also witnessed by JJMA personnel, one canopy arch inflation was conducted using the arch compressed air cylinder. The arch inflated within two seconds.) The raft was then removed from the pool, deflated, and transported back to the SWITLIK plant for the remaining inflation tests, which were conducted dry. These were quality control tests designed to assure that the raft was free of leaks and that the inflation system functioned properly.

The raft performed satisfactorily during all the tests witnessed.

5. SEA TESTS

Sea tests, as a means of validating the capsize performance of a raft, cannot be faulted in principle. The 1994 NPRM (Reference 4) called for a 6-hour aggregate exposure to 15 feet minimum significant wave height and 40 knot winds. The raft must be observed during the entire exposure, and must not capsize. Without question this would be a demanding and expensive test to perform.

However, even in principle, the specification of seastate and exposure time does not completely determine primary quantities related to raft capsize in extreme waves, namely, the prevalence of sharp crested and/or breaking waves, and their geometry. A breaking wave needs at least three numbers to describe it even approximately: height, celerity, and steepness (or type of breaking). A breaking wave <u>encounter</u> needs an additional piece of information: phase. The severity of an encounter, in some sense, should be determined by all of these factors, but the relationship is extremely complex. More to the point, the number and severity of encounters with breaking waves can vary tremendously, even in seas which can all be characterized as having significant heights of 15 feet or more.

Nevertheless, at-sea testing under some conditions is an excellent way of acquiring videotaped records of breaking wave encounters, which can be of value in assessing the behavior of a raft, even if the test is not required by regulations. In the case of "side-by-side" tests of two dissimilar rafts, further information can be gained by direct comparison. Finally, at-sea tests also provide vital information on drift rates, both empty and with a simulated load..

5.1. Preparations

Side-by-side drift and seakeeping tests were conducted on two different life rafts, the existing reversible raft and the prototype Switlik 20-Man SAR raft. Tests were conducted off San Francisco. Preparations for testing began on 21 March 1997 at the USCG Buoy Depot, Yerba Buena Island, and on board USCGC BUTTONWOOD.

The 20-person reversible raft is currently used on HC-130 aircraft. This raft can be used with either side up, and has neither water-filled ballast bags nor a canopy. It is twelve-sided, with a nominal outside diameter of approximately 12 ft 3 in across opposite corners. The raft floor is attached to the junction of the two main buoyancy tubes. The center of the floor is supported by an additional 3-ft diameter inflatable floor support ring, which is manually inflated after boarding. Inflatable boarding slides are attached at opposite sides of the raft, one directly inflated from the lower buoyancy tube, the other from the upper tube. The single inflation bottle delivers to both buoyancy tubes via a Y-shaped fitting and two check valves. The two buoyancy tubes are connected by a pressure equalization hose, which is normally manually clamped after inflation to provide two separate buoyancy chambers. For the purposes of this report section, this raft is referred to as the "old" raft. A sketch of this raft is shown in Figure 2.

The prototype 20-Man SAR raft, built by Switlik Parachute Company, has a rounded rectangular planform, approximately 12 ft 7 in length and 8 ft 6 in breadth. The raft floor is

attached to the bottom of the lower buoyancy tube, without central support. The raft is fitted with six water-filled ballast bags of approximately 3 ft^3 capacity each, measured below the level of the large flooding openings around the inboard and end surfaces of the bag, near the top. Three strap-type boarding ladders with batten-stiffened foot rungs are suspended from each side of the raft. Two independent inflation bottles are fitted, one for each buoyancy tube.

The raft is equipped with a full canopy, supported by two inflatable arches. Each arch can be erected using either a compressed air bottle or by inflation by mouth. The canopy is made up of two end sections, permanently attached to the arches, a top panel attached to one end section and secured to the other by a zipper and lashings after erecting, and two side panels to close the spaces between the canopy top and the upper buoyancy tube. For convenience, this raft is referred to in this section as the "new" raft, Figure 3.

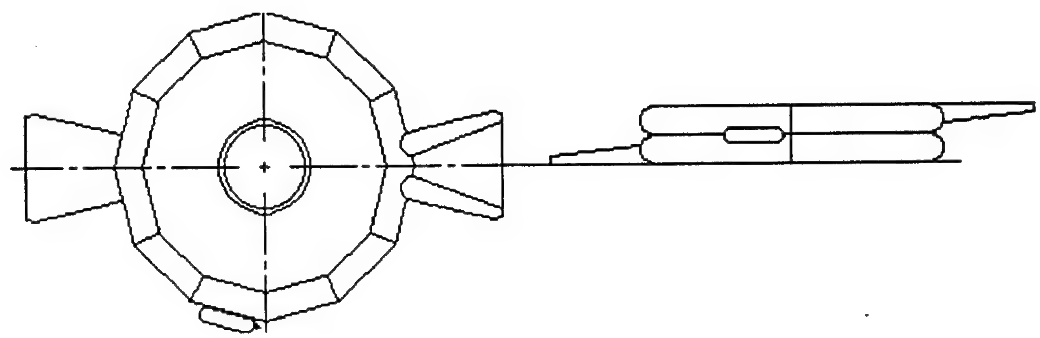

Figure 2. Sketch of Existing ("Old") Raft.

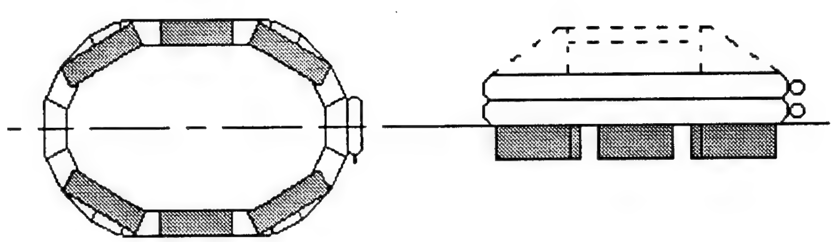

Figure 3. Sketch of Prototype ("New") Raft.

As the rafts were to be tested both empty and loaded with weights to simulate occupants, it was necessary to fabricate plywood and lumber strongbacks to fit both rafts. Scrap buoy chain was used as weight, allowing each raft to be loaded with 1800 pounds, including chain,

strongback assembly, bilge pump, battery and instrumentation package, but not including the weight of the raft itself. Chain was cut to length and lashed into four chain boxes provided on each strongback. Construction and ballasting arrangements were completed on 25 March 1997. The following day, due to very light wind and low wave height conditions, at sea testing was postponed and rescheduled for Thursday, 27 March 1997.

The unloaded drift tests were designed primarily to compare the tendencies of the two rafts to drift away from survivors before they can be boarded. No instrumentation was placed aboard the rafts. Rather, the global positioning system (GPS) aboard the buoy tender which conducted the tests was used to record the latitude and longitude of each raft at the beginning and end of each test. Two side-by-side tests, each approximately 45 minutes long, were conducted. The canopy on the new raft was not deployed. In the first test, the rafts were launched without deploying the drogues supplied with each raft. Before the second test, one raft was towed to the same starting position as the other, and both drogues were deployed. In addition to the GPS measurements which provided speed over ground during each test, videos of both rafts were taken, and qualitative observations of their performance were recorded.

The seakeeping tests were designed to compare the drift and seakeeping characteristics of the two rafts when loaded with weight equivalent to ten persons (1800 lbs), supported by the plywood strongback, which in turn was lashed to the raft so that it would not pull out during deployment and recovery.

Instrumentation included a "mission data recorder" (MDR) which recorded the time, vertical acceleration amidships, pitch angle and roll angle, each at 0.25 second intervals. (Additional description of the MDR is given in Report CG-D-20-94, "Coast Guard Mission Data Recorder for the 47-FT Motor Lifeboat", 1994). (Provision was also made for the MDR to record tension readings from a load cell connecting the drogue to the raft, but the load cells were damaged during raft deployment so no measurements were actually obtained). Other instrumentation included a current meter, trailed from the upwind side of the raft, which recorded the magnitude and direction of the speed through the water. Each raft was also fitted with a 12 volt battery power supply, and a bilge pump with strainer positioned at the raft's center. GPS measurements were also taken at the beginning and end of each test to provide speed over ground.

5.2. Test Visual Observations

Both rafts, their strongbacks, chain loads, and instrumentation were loaded aboard the 180 ft WLB buoy tender USCGC BUTTONWOOD on Thursday, 27 March 1997, and transported to a location between the shipping lanes approximately 10-15 miles outside the entrance to San Francisco Bay. The ship's rigid inflatable boat was launched as a support and chase craft. The first drift test was initiated next to NOAA data buoy 46026 (37.75 N, 122.82 W) which provided measurements of wind speed and direction, significant wave height and wave spectra, during the tests. Subsequent tests were initiated as the rafts continued to drift downwind, but observations aboard ship confirmed that weather conditions throughout the tests remained nearly the same as those at the NOAA buoy. The conditions at the start of tests were approximately 14 knots

westerly wind, with 7 ft significant seas, gradually building during the day to over 23 knots northwesterly wind and waves over 9 ft significant.

Test 1: Both rafts were launched, unloaded, with no instrumentation and without drogues, and released in close proximity to one another. They were allowed to drift for approximately 45 minutes, during which the flat raft was seen to become partially airborne approximately 10-20 times, and flipped over at least 3 times. During this same period, the new raft never left the water surface. After a half hour, the old raft was almost three times further from the starting point than the new raft.

Test 2: After the first drift test, the rafts were towed back together and their drogues were deployed. They were then allowed to drift as before.

The prototype raft showed no obvious differences in behavior, but the old flat raft's behavior seemed worsened rather than moderated by the presence of the drogue. Observers concurred that the old raft with the drogue appeared "even more unstable" with drogue than without. It flipped over at least 5 times, and one end lifted out at least 80 times. Occasionally, the entire raft lifted out of the water, becoming airborne like a kite, and at times pivoting about the inflated boarding slides. In appeared that the presence of the drogue line tension on the windward side of the raft provided a tether similar to a kite string, and in fact increased the raft's tendency to remain completely airborne for several seconds at a time.

During this same period, the new raft continued to contour the wave, and never left the water surface. After a half hour, the old raft was two and a half times further from the starting point than the new raft.

Test 3: The rafts were then recovered on deck to fit out for loaded tests, with drogues, and with strongbacks, chain weight, and instrumentation installed. Because of the time required to install the ballasted strongbacks and launch the rafts, under challenging sea conditions, the two rafts could not be launched as close together as desired, although the effort was made to launch the second raft as close as possible to the first one. During deployment, the old raft swung hard into the side of the WLB in the vicinity of the current meter. This impact was later determined to have disabled the current meter.

Loaded, neither raft displayed a tendency to capsize or blow over. The new raft appeared to be riding more easily than the old raft, but both rafts remained on the water surface. At the end of 1 hour, the new raft was about 1/4 nautical mile downwind of the old raft.

Test 4: The second loaded test was made without drogues, and the starting positions of the rafts were taken to be where they lay rather than attempting to tow them closer together, because of the difficulty of towing the heavy rafts with the ship's rigid inflatable boat in the sea conditions. As a result, it was difficult to form a very accurate impression of their relative drift rates until the position data became available at a later date. However, from visual observation there appeared to be little difference in drift rates. Differences in drift rate measured during this test are subject to doubt because of the separation between the rafts, and the fact that the current meter on the old raft was disabled. However, positions for both rafts were taken at the beginning and end of each run by taking a bearing and distance from the BUTTONWOOD's bridge to the raft and a position fix from the cutter's GPS unit.

Even without the drogues, both loaded rafts continued to contour the surface. Neither displayed a tendency to capsize or become airborne. Nevertheless, the new raft appeared to be riding more easily than the old raft.

5.3. Weather Conditions and Test Schedule

A summary of weather conditions recorded by the NOAA data buoy during the test is provided in Table 3. The conditions and the starting and finishing times for each test segment are given in Table 4. Wave spectra from the NOAA buoy during the tests are shown in Figure 4.

5.4. Measured Results

Using GPS positions at the start and finish of each test, the distance and direction traveled over the ground could be obtained. Dividing these distances by elapsed time gave speed over ground. For tests 3 and 4, the average speed through the water and direction were computed from the leeway meter data. Since the vector sum of the leeway speed and the current velocity must equal the speed over ground, the current velocity and direction could be deduced.

However, the current meter data on the old raft appeared very erratic, probably due to the hit it took during deployment. Thus, it was decided to assume that the current vector obtained from the new raft during each test could also be applied to the old raft, allowing leeway vectors to be deduced for the old raft. Any actual differences in the current vector between the positions of the rafts, which had drifted apart, would introduce some uncertainty into these results. The vector speed diagrams for tests 3 and 4 are shown in Figures 5 and 6, respectively.

Heave, pitch and roll data from the mission data recorders for tests 3 and 4 were also analyzed. The mean value of each data channel was computed. After the first upcrossing of the mean line, the highest peak before the next downcrossing was found. The lowest trough between this downcrossing and the next upcrossing was found. Thus all peak-trough distances in the record were tabulated, and sorted into descending order. From this, the following peak to trough statistics were easily obtained: maximum, average of highest 1/10, average of highest 1/3, and the average. These data, along with the magnitudes in knots of speed over ground (Vog), current speed (Vc), and speed through the water (Vr) are summarized in Table 5.

Table 3. Weather Conditions During Tests.

NOAA Buoy 46026 Data, 27 March 1997

PST	Wind Speed (kts)*	Wind Direction	Sig Wave Height (ft)
12:00	13.6	290	6.9
13:00	17.5	300	7.5
14:00	19.4	310	7.2
15:00	21.4	300	8.2
16:00	21.4	300	8.9
17:00	23.3	300	9.2
18:00	23.3	300	9.2

* Wind speeds on this data buoy were measured 5 meters above the surface.

Table 4. Test Schedule.

Test #	Raft	Condition	Start Time (PST)	Finish Time (PST)
1	Old	Empty, w/o drogue	12:05	12:37
	New	Empty, w/o drogue	12:05	12:44
2	Old	Empty, with drogue	12:53	13:23
	New	Empty, with drogue	12:53	13:30
3	Old	Loaded, with drogue	14:54	16:01
	New	Loaded, with drogue	14:54	15:35
4	Old	Loaded, w/o drogue	16:01	17:35
	New	Loaded w/o drogue	15:56	16:56

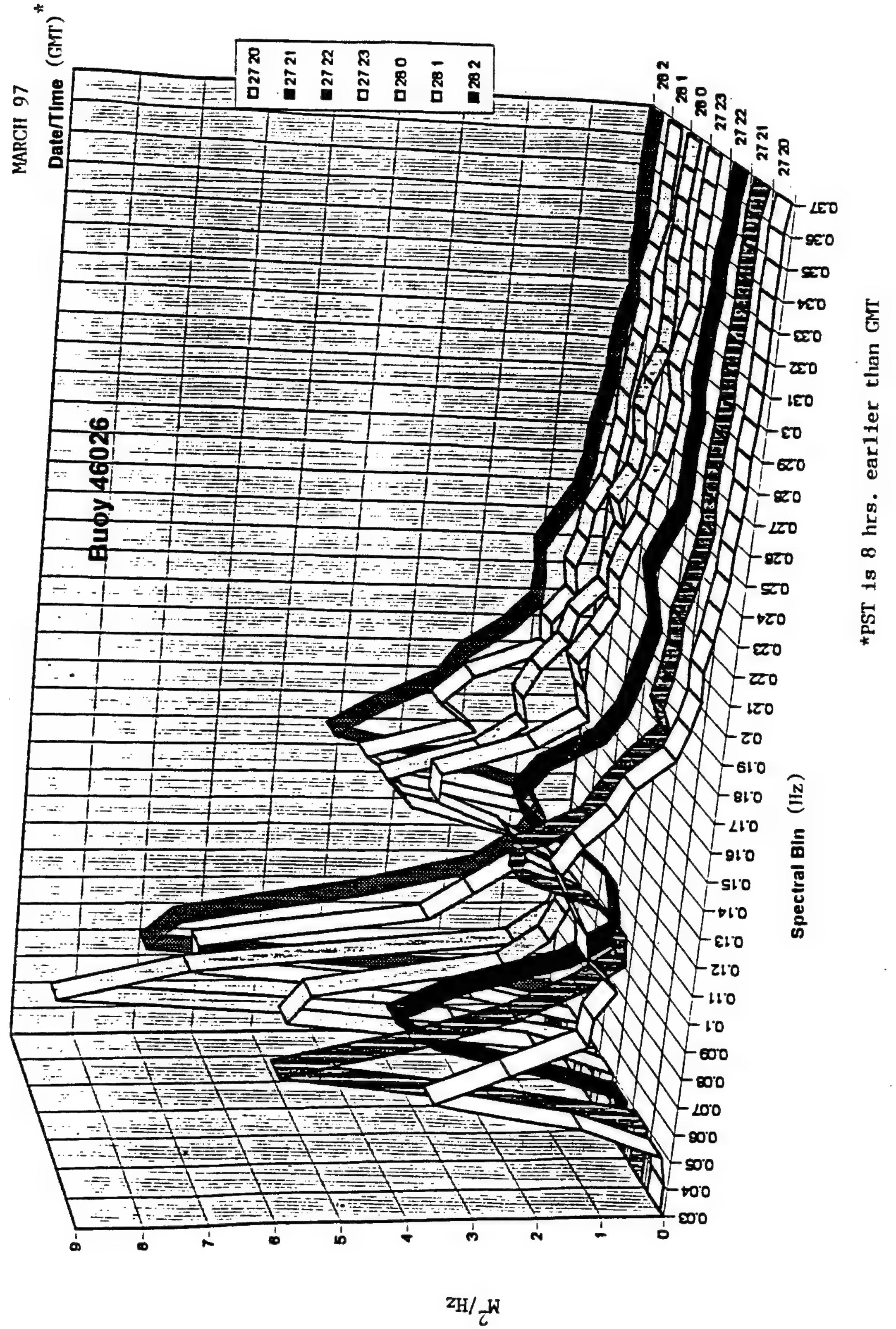

Figure 4. Sea Spectra during Tests.

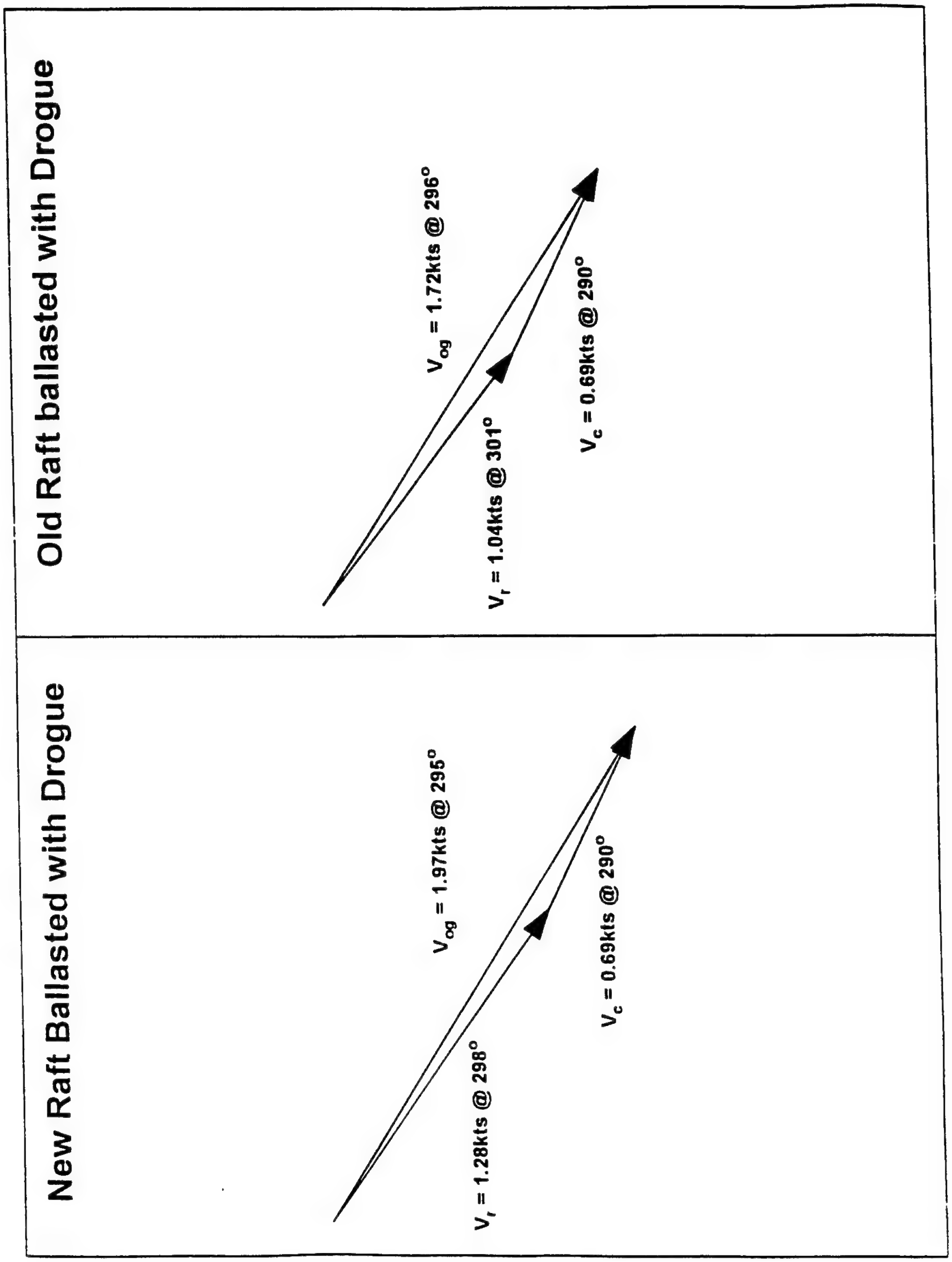

Figure 5. Drift Results with Drogues.

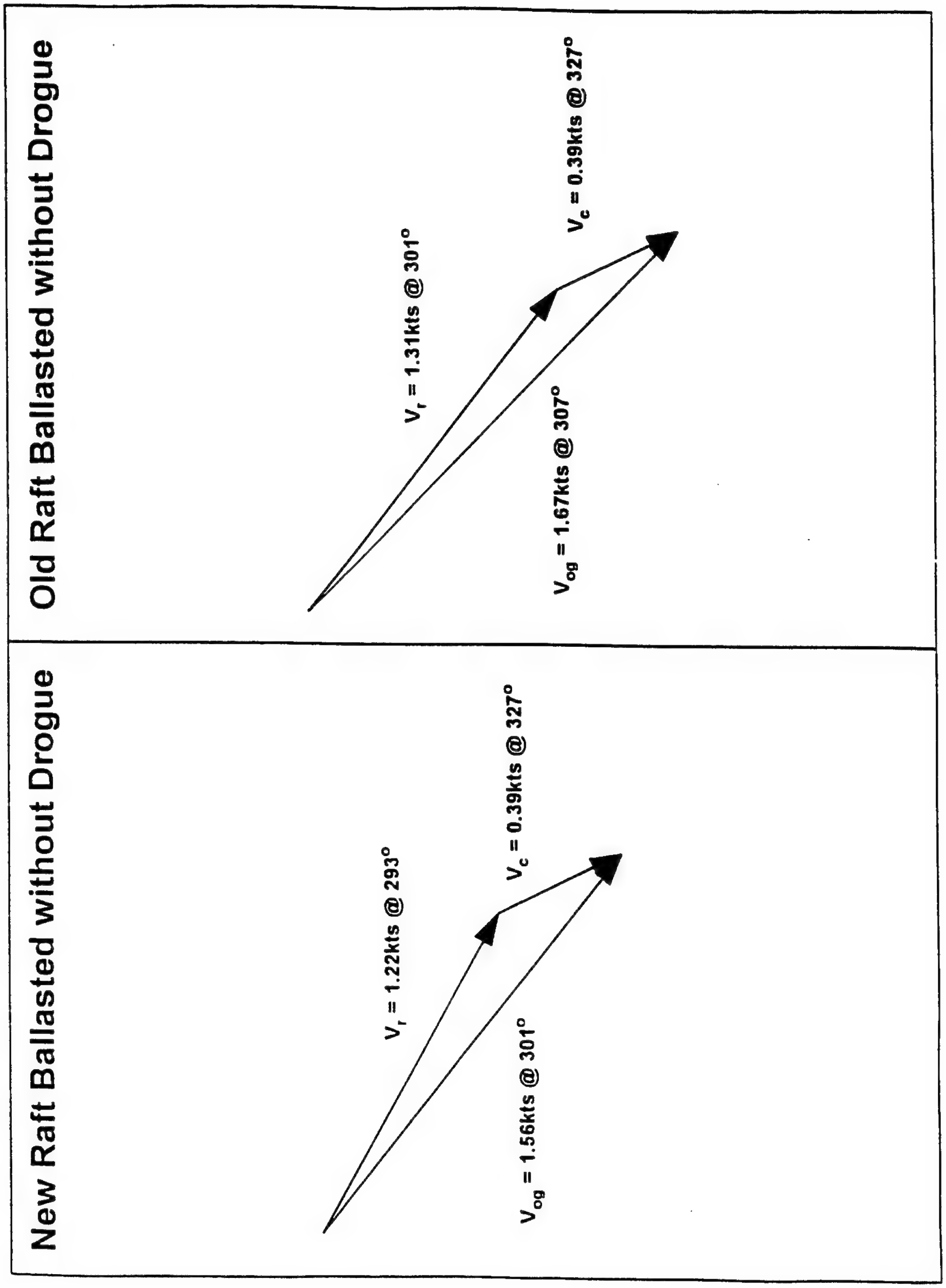

Figure 6. Drift Results without Drogues.

Table 5. Summary of Sea Test Results.

EMPTY CONDITION	WITHOUT DROGUE		WITH DROGUE	
	OLD RAFT	NEW RAFT	OLD RAFT	NEW RAFT
Vog (kt)	1.85	0.69	2.18	0.89

LOADED CONDITION	WITHOUT DROGUE		WITH DROGUE	
Vog (kt)	1.67	1.56	1.72	1.97
Vr (kt)	1.31	1.22	1.04	1.28
Vc (kt)	0.39	0.39	0.69	0.69
Heave acceleration (g's)				
mean	0.22	0.22	0.23	0.22
h 1/3	0.34	0.36	0.35	0.35
h 1/10	0.43	0.45	0.44	0.44
max	0.81	0.68	0.63	0.68
Pitch (deg)				
mean	2.59	1.37	2.69	1.58
h 1/3	4.31	2.12	4.43	2.69
h 1/10	6.14	3.61	6.02	4.18
max	26.00	16.00	12.00	9.00
Roll (deg)				
mean	2.76	2.61	2.96	1.76
h 1/3	4.74	3.96	4.76	2.51
h 1/10	7.53	6.83	6.94	3.68
max	54.00	53.00	21.00	6.00

5.5. Discussion

In the empty tests, tests 1 and 2, the old raft's speed over ground was roughly three times that of the new raft, both with and without the drogue. The old raft's speed would have made it difficult for a swimmer to catch up. For both rafts, the speed over ground increased during test 2, with the drogues, probably because the wind speeds were slightly higher. However, the erratic airborne behavior of the old raft with drogue may have also reduced the drogue's effect.

In the loaded tests, tests 3 and 4, the old raft had slightly lower speeds over ground and, subject to the assumption of the same current acting on both rafts, speed through the water than the new raft, both with and without the drogues attached. The effects of the drogues on each raft's speed over ground and mean speed through the water were small, though the new raft showed slightly higher mean speed with the drogue than without, which is unexpected.

Heave values for both rafts were nearly identical, both with and without the drogues. The drogues did not affect heave significantly. Pitch and roll values were consistently higher for the old raft than the new raft, both with and without drogues. On both rafts, the relatively large maximum pitch and roll values suggest that these processes did not follow a Rayleigh distribution. These maxima were significantly reduced by the drogues. (It is significant to note that the maxima occurred at very different times, indicating that they are not the result of a single unusually large wave). Since these are peak-to-trough maxima, neither raft was likely to capsize in these sea conditions.

6. LIFT-OUT TESTS

6.1. Preparations

After their use in sea tests, the two rafts described in the previous section were subjected to lift out tests in accordance with Reference 4. The rafts were inflated for testing on 12 June 1997. It was noted at that time that the old raft was holding pressure well, except for a minor leak in the inflatable floor support ring. This leak was judged to be inconsequential to lift-out force tests, as the floor support was still effective and did not contribute to the over-all rigidity of the raft.

However, on the new raft, both buoyancy tubes were losing air, the upper tube faster than the lower. No manometer was available at that time to check maximum inflation pressure or leakage rate. Both rafts were lift-out tested, with results given in the next section. However, because of the air losses in the new raft, both the force record and the video recording show that the raft was too soft during the tests to give reliable results.

Once afloat, with personnel aboard to hand pump the tubes to continue testing, damage was observed in the raft floor -- a 3/4-inch seam gap in the forward floor seam, admitting water into the raft. This was temporarily repaired to continue the test, in spite of the air losses from the tubes.

A water manometer was rigged and the new raft inflated to 42 inches of water. Pressure loss rate from the upper tube was found to be approximately 10 percent in 6 minutes; lower tube about 10 percent in 10 minutes. A search for buoyancy tube air leaks was conducted, and none were found. The inflation cylinders were unwrapped entirely from their fabric sleeves and bags, and inspected. Both cylinder bleed valves were found to be partially open. These bleed valves are intended to equalize air pressure when the raft is stowed in an aircraft and subjected to widely varying atmospheric pressure. For this reason, they must remain open in flight, and cannot be spring-loaded or safetied closed. Normally, when the raft inflation cylinders are triggered, the bleed valve is forced closed by cylinder pressure, and then remains closed under raft pressure and by the valve's own internal friction.

However, during handling of the raft, whether after the sea tests, in shipment, or during inflation for the lift-out tests, it appears that both bleed valves were depressed (opened) and could not reseat themselves under raft tube pressure alone. When the bleed valves were identified as sources of air loss, for the purposes of lift-out tests the inflation tubes were disconnected from the inflation cylinders and temporarily plugged. The inflation cylinders, however, were left in their bags and sleeves on the raft buoyancy tubes in order to test the raft in the required weight condition.

This detail of the bleed valve is <u>not</u> considered a flaw, as the location of the valve makes it unlikely to be inadvertently reopened after raft inflation, provided that the cylinders are properly wrapped and secured on the raft. (The bleed valve is recessed in a relatively protected space

between the underside of the inflation valve assembly and the head of the cylinder.) Nevertheless, this is an item to check during raft packing, as improper location of the small line tying the cylinder into its wrapping could conceivably press on the bleed valve button and cause it to open after raft deployment.

The bleed valve could also be more securely held in its closed position (after inflation) if it engaged more positively, either with more friction or with a mechanical safety, such as a spring-clip. It should be noted that if a bleed valve is inadvertently opened, after inflation, the only way to close it, at present, is to remove the inflation tube from the cylinder valve assembly and push the bleed valve closed from inside. This would be difficult or impossible at sea. However, the raft manufacturer's experience has shown that the bleed valve has not led to problems of air loss in use.

After this adjustment, the leakage rate test was repeated, and their was found to be little or no air loss. The lift-out test was then repeated on the new raft, inflated into the range of normal working pressures, approximately 48 in of water.

6.2. Lift-Out Test Procedures

The rafts were tested in an outdoor swimming pool in 10 to 12 ft water depth. Wind was not a factor. A simple wooden A-frame was constructed to provide a hoisting point for a 6:1 tackle. Hoisting forces were provided by man-power on the tail of the tackle. Speed measurements were taken videographically, directly observing a mark on the moving block of the tackle against a calibrated vertical pole (white PVC with black markings at 1 ft intervals) suspended from the A-frame. This setup, though extremely simple, proved capable of repeatable hoisting speeds at the required rate, for the short durations of the lifts, using only one or two men walking with the tail of the line.

Forces were measured directly, using a load-cell between the moving block of the tackle and the raft lifting bridle. Time histories of the load cell force were recorded on a strip chart.

The lifting bridles were attached to existing attachment points on both rafts. In the case of the old raft, two lifting straps were used. For the new raft, lifts were made from the bow (opposite the inflation cylinder end, which is the heavier end), and from one side. Three lifting straps were used as attachment points for the bow-on tests, and the attachment points of the boarding ladders for the athwartships lift-out.

6.3. Results and Discussion

The lift-out force test results are summarized in Table 6. Results with the old raft were as expected. A very low lift-out force, not exceeding 30 lb, which is about half the raft's weight, was recorded, and the raft showed very little deflection during the test.

It was noticed, however, that depending on the speed at which this raft was lowered onto the water surface, enough air could be trapped under the floor to cause it to remain "domed" by several inches, convex up, with the central "floor support" buoyancy ring completely clear of the water. Normally, when the raft was placed gently on the surface, the floor was quite concave, resting on the floor support tube, which was afloat.

In order to determine whether air-pressure conditions under the raft floor had any effect on the lift-out force result, the raft was lifted-out in the so-called "floor-inflated" condition for comparison. The results with the "floor inflated" showed a repeatable and surprisingly large increase in the maximum lift-out force, above the normal result. This seemed counter-intuitive, until it was realized that over-pressure in the air space under the floor results in a jet of air emerging under the buoyancy ring when it clears the water surface. The release of this jet was audible, and it could also be felt as a burst of warm air, the air under the floor being warmed in contact with the sun-heated floor of the raft. The pressure in this emerging jet is lower than atmospheric, and acts on a significant part of the undersurface of the buoyancy tube on the hoisted side.

The jet is transient, the entire "spike" lasting less than half a second. However, its peak magnitude represented approximately a 30 percent increase in maximum lift-out force, versus the tests in which the raft had been placed slowly on the surface. In practical terms, the variation of lift-out result due to air-pressure under the floor can be of no significance whatsoever in capsize resistance.

The new raft was lifted out from the side and from the bow. Lifted from the side, the lift-out force was 250-260 lb. Lifted from the bow, a lift-out force of 260-275 lb was obtained. It appeared that water was draining from the ballast bags more rapidly than expected, and that this drainage prevented the lift-out force from being even higher. However, there is a compromise between drainage rate and rapid flooding of the bags when the raft is deployed or righted. Consequently, without further testing of alternative bag designs, there is insufficient basis for recommendations.

The raft's upper buoyancy tube buckled slightly during liftout from the bow, but returned to an unbuckled shape as the ballast bags drained. It is concluded that the bow bags contribute most of the lift-out force. On the grounds of raft geometry, it could be estimated that the middle bags only contribute about one-quarter as much as the bow. However, because each bag has filling holes on the inboard and end panels, it may also be that the middle bags drain faster because of their essentially fore and aft orientation on the raft. Again, without testing of alternatives, there is no reason to suggest any changes.

Table 6. **Summary of Lift-Out Force Test Results.**

Old Raft: Diameter B = 11.2 ft
Total Hoist = B sin 20° = 3.83 ft
Target Hoisting Rate = 5.5 B = 61.6 ft/min = 1.03 ft/sec

Run	Speed (ft/sec)	Maximum Force (lb)	Comments
1	No data	No data	Rig check
2	0.94	27	Slow lift
3	0.93	25	"
4	0.90	26	"
5	0.99	28	Target speed run
6	0.99	37 Spike	Raft Floor "Inflated"
7	0.99	35 Spike	Raft Floor "Inflated"
8	0.99	28	Target speed run

New Raft, Lifted at Side: Breadth B = 8.5 ft
Total Hoist = B sin 20° = 2.91 ft
Target Hoisting Rate = 5.5 B = 46.8 ft/min = 0.78 ft/sec

Run	Speed (ft/sec)	Maximum Force (lb)	Comments
1	0.81	263	Raft Pressure 48" water
2	0.81	250	
3	0.69	240	Slow hoist

New Raft, Lifted at Bow: Length B = 12.5 ft
Total Hoist = B sin 20° = 4.28 ft
Target Hoisting Rate = 5.5 B = 68.8 ft/min = 1.15 ft/sec

Run	Speed (ft/sec)	Maximum Force (lb)	Comments
1	1.05	262	Raft Pressure 48 inches of water
2	0.97	168	Did not wait for bags to refill fully
3	1.00	230	
4	1.05	255	
5	1.20	275	
6	Very slow	81	To estimate low-speed limit

6.4. General Comments

The tests showed that the ballasted raft had lift-out forces on the order of ten times greater than the unballasted reversible raft. In general, lift-out force tended to increase with hoisting rate. The major influence limiting lift-out force from the ballasted raft appears to be the rate of drainage from the ballast bags as they are lifted out of the water. As might be expected, when a raft is lifted very slowly the contribution of the ballast is greatly reduced by drainage.

However, at hoisting rates near the rate prescribed in Reference 4, there is considerable scatter in the data from run to run, which cannot be ascribed solely to variations in hoisting rate. It is judged that much of this scatter resulted from variations in the shape and "fullness" of ballast bags, which is affected by the waiting time and agitation of the bags between runs.

The most obvious way to increase lift-out force, as measured by the procedures of Reference 4, is to increase the total capacity of ballast bags and to reduce the rate of drainage. In this connection, it appears that the condition of the ballast bag fabric and seams may be an important factor in the result. In particular, drainage could be increased dramatically by scuffed or damaged coatings of the bag fabric, and by opened seams. Further, rearrangement of the filling openings may also reduce the rate of drainage.

As a means of increasing ballast bag effectiveness by capacity, it is judged that the effects of increasing aggregate area of bags in planform, as opposed to their depth, would be different for the side-hoist and bow-hoist directions, for non-circular rafts. Because of the smaller required hoist in the sideways direction, an excessively deep bag would not completely emerge in this direction of hoist, so its additional capacity would not necessarily become fully effective in the test.

6.5. Comparison with Proposed Rule Requirements

Reference 4, paragraph 160.151-29, incorporates a formula for minimum acceptable lift-out force. This "Proposed Rule for Inflatable Life rafts," has not yet been promulgated as of July 1997, and was not intended, as written, to apply specifically to aviation life rafts. Nevertheless, a comparison with the proposed requirement is interesting.

The proposed rule equation for minimum acceptable lift-out force is:

$$F = 58 + 32\,P - 0.16\,P^2\,, \qquad \text{[Eq 3]}$$

where F is the peak lift-out force (lb) and P is the number of persons for which the raft is to be approved. For a non-circular raft, this force is to be provided as a minimum in both directions, fore-and-aft, and athwartships. For a 20-man life raft, the required value of F is 634 lb. Neither raft achieved this value. However, the new ballasted raft obtained over 40 percent of this value, while the existing raft obtained 4.4 percent.

Reference 4, paragraph 160.151-17, also includes a required value for the combined capacity of water-containing stability appendages. The combined volume of ballast bags (measured to the lowest opening in the bag) is not to be less than 2.85 P (ft^3). Accordingly, for a

20-man raft, the required combined volume of ballast appendages under this paragraph is 57 ft^3. The prototype 20-man SAR raft has six ballast bags, each of approximately 3 ft^3, for a total of 18 ft^3. It is therefore not surprising that the raft did not generate lift-out forces in accordance with the requirement of Reference 4, paragraph 160.151-29, since it was not required to have stability appendages in accordance with paragraph 160.151-17. In any case, the available space in the HC-130 wing well precluded the use of additional or significantly larger ballast bags.

7. CONCLUSIONS

7.1. Comparative At-Sea Tests

On the basis of comparative tests with the old and new rafts, it is clear that the new raft offers significant advantages in survivability over the old one. The following specific conclusions are drawn:

(1) The new raft, unloaded, has significantly less drift, and would be easier for a swimming survivor to reach than the old raft.

(2) Over-all, even with drogues deployed, the new raft is considered less likely to capsize in severe seas than the old raft, by a significant margin, especially when lightly loaded.

(3) When loaded, both rafts have similar heave response, but the old raft pitches and rolls more severely than the new raft.

(4) The drogue apparently reduces the roll response of the new raft mainly by holding it head to the waves, since the pitch responses measured at 1/3 and 1/10 highest levels actually increased. It is significant, however, that the drogue reduced both pitch and roll responses of both rafts, when measured at the maximum values. It must be concluded that a drogue is most effective in limiting large excursions due to wave or windage forces, and has less influence on general ride qualities measured closer to the mean.

(5) The new raft rode more easily in pitch and roll, with or without a drogue, as measured at 1/3 or 1/10 highest levels, but reached essentially the same maximum values as the old raft. The exception, in roll, shows the effect of the drogue on the new raft by holding it head to sea.

7.2. Lift-Out Force Tests

On the basis of comparative lift-out force tests with the old and new rafts, the following conclusions are drawn:

(1) The ballasted raft had lift-out forces on the order of ten times greater than the unballasted reversible raft.

(2) Neither raft achieved the required value of lift-out force specified in the NPRM, Reference 4. The new raft obtained over 40 percent of this value, while the old raft obtained only 4.4 percent. The NPRM has not been promulgated as a rule, and was not invoked for application to aviation rafts. The new raft has approximately 18 ft^3 of water ballast, which is approximately 31 percent of the ballast required by Reference 4. The old raft, of course, has none.

(3) FAA standards, which are applicable to aviation rafts, do not currently mandate a lift-out force requirement, although there must be water pockets or other means (unspecified) to provide capsize resistance for an empty or lightly loaded life raft.

7.3. Capsize Behavior

Capsize behavior in extreme sea conditions is an exceedingly complex nonlinear problem regardless of the body considered. For inflatable life rafts, the dynamic responses of the body, including its buoyancy chambers, ballast appendages, and canopy, if any, are even more complex, since they all involve potentially large deformations under capsizing loads, non-rigid body responses of the most massive parts of the system (overwhelmingly composed of ballast in essentially flexible appendages, and raft occupants), and downflooding of the passenger compartment. The internal flow of ballast water within flexible appendages, especially if they are relatively large, makes even the determination of effective inertia extremely difficult, Experience has shown that relevant capsize mechanisms involve not only hydrodynamic but aerodynamic forces which cannot be neglected, and are generally not independent. The effect of other external forces, notably drogue forces, on wave and wind interactions which may lead to capsize events, is also highly complex.

A comprehensive theoretical treatment of life raft capsize does not exist. Further, current numerical hydrodynamic tools are not equal to the task of predicting responses in extreme waves, even for bodies considered as rigid, except under simplifying assumptions which are not realistic for life rafts. The theoretical literature of highest, steepest, or extreme waves, including breaking waves, is of use in systematizing the description of various capsize mechanisms. Nevertheless, none of the models of extreme waves leads to a generally useful predictive tool for life raft capsize. The anecdotal literature of yacht and life raft capsize is extensive, but it also does not offer a reliable predictive tool. In many cases, this part of the literature is characterized by imprecise terminology and conflicting claims, many of them attributable to bias.

The following over-all conclusions have been reached as a result of critical review of the literature, theoretical, empirical, and anecdotal:

(1) The importance of raft stability, understood in the strict sense of restoring moments and their integrals with respect to inclination angle, is often overstated. In steep waves characterized by a plunging breaking crest, static stability is not an asset against capsize; stability in effect makes the raft follow the inclination of the wave surface and leads to capsize.

(2) With a few notable exceptions, the importance of inertia to capsize resistance is not sufficiently emphasized. Overwhelmingly, life raft capsize occurs due to interactions which are local to an individual wave crest, or the result of breakdown of a wave crest. These interactions may be characterized in most cases in one of four ways:

(a) <u>Interaction of a raft passing over a wave crest near the limit of breaking</u> (the so-called steepest wave). The capsize mechanism generally involves aerodynamic (windage) forces, especially lift and pitching moment, which grow with exposure of the rafts undersurface and angle of attack. The entire response leading to capsize occurs over a time scale which is much shorter than a wave period. The motion leading to capsize is highly nonlinear. The raft often becomes partially "unweighted" or airborne. Its stability (restoring moment) and hydrodynamic resources (damping and added inertia) are consequently temporarily reduced at the critical moment of the wave encounter, residual

overturning moments or angular velocities cannot be adequately resisted or damped, and capsize results.

(b) Interaction of a raft with a spilling breaker, at some distance down the face from the crest. The spilling breaker is characterized by a layer of aerated water accelerating ahead of the crest and thickening as a result of turbulent entrainment of water from the face of the wave. The depth, velocity, and vorticity of the front of the layer increase for a time as the "gravity current" accelerates down the face of the wave, and then begins to attenuate as it runs out onto less steeply sloped regions of the surface toward the trough. The response of a raft in an encounter with the breaker front depends on the location down-slope. If the encounter location is high on the wave, the front may not have thickened or accelerated sufficiently to cause capsize. By contrast, if the encounter occurs too far into the trough, the layer may have decelerated and dissipated enough to lose its energy and the encounter is ridden out without capsize. Between these two phases of the breaker, the front represents a maximum overturning impulse. Stability, especially righting energy, is an asset against capsize, but in a deep, fast-moving front may be inadequate. The capsize mechanism may be understood as resulting from the shear velocity between the spilling breaker front and the underlying face of the wave, which has not yet been entrained by the aerated layer. Consequently, the overturning moment may also grow as the raft inclines, presents a larger area, and is exposed to higher velocity differences across the depth of the layer behind the front. The response leading to capsize is nonlinear.

(c) Interaction with a plunging breaker jet. The capsizing response is initiated by the impact of a jet of water emerging from the crest. In plunging breakers, the velocity of the jet may be several times greater than the phase velocity of the parent wave. The nature of the interaction is critically affected by location of the raft on the face of the wave, and the scale of the breaking crest, both of which determines the location of the jet's impingement on the raft. The jet, if it impacts the canopy or body of the raft with a large horizontal component of velocity, will deform it. Depending on the nature of this deformation, the over-all momentum transfer from the jet may be increased or decreased. Because of the high velocity of the jet, the force increases impulsively, on a time scale which is short with respect to wave period. Stability, specifically righting energy, is an asset against capsize, but if the jet is intense it may be inadequate. Further down the face, the jet will fall to a trajectory closer to the vertical, or it may have re-entered the face of the wave and reorganized itself as a shear flow similar to a spilling front. Further up the face, the jet may pass over the top of the raft, and the result may become a large excursion around the interior of the plunging breaker, collapse of the face of the breaker onto the raft, or a combination of the two, depending on the scale of the breaking crest with respect to the size of the raft. In principle, increased static stability will make the raft incline along with surface of the wave; increased inertia will tend to slow this response, resulting in more penetration of the wave's surface while the breaker has time to collapse on the raft.

(d) Interaction with the interior of a large plunging breaker. Capsize occurs without the raft inclining with respect to the local surface. The raft becomes inverted along with the interior of the breaker and is delivered in essentially free fall to rejoin the

wave face, surrounded by the collapsing breaker. The subsequent motion of the raft within the shear flow formed by the spilling remains of the breaker is problematic.

7.4. Drogues

The following conclusions are drawn with respect to drogues:

(1) The effect of a drogue on the above capsize mechanisms is to provide a counter-capsizing moment which increases with large inclinations, and a force which pulls the raft over or through the crest more quickly. This may reduce the time during which the raft is exposed to windage or shear-velocity forces, and consequently the total capsizing impulse. An effective drogue is considered an important adjunct to the raft' s own stability and inertia, but not a substitute. Even in studies which supported the effectiveness of drogues in general, it was found that increased ballast capacity improved life raft capsize resistance, largely by virtue of inertia.

(2) For a rectangular planform raft, the drogue acts to advantage by helping to orient and hold the raft bow to sea and/or wind. A drogue's action and effectiveness, however, is not isotropic. For this reason, drogues are considered less effective in confused seas, and where wind and waves may be from different directions. Ballast, being a primary repository of total inertia in both angular modes, is less influenced by directional confusion.

(3) For a light unballasted raft, which is more susceptible to being lifted out of the water by windage forces and moments, a drogue alone may not be sufficient to improve performance. In sea-tests performed as part of this study, the observation was made that drogue tension actually increased "kiting" and apparently unstable airborne motions of the old (unballasted) raft, when empty.

(4) A drogue's effectiveness can be destroyed by fouling in its own bridle, or by damage. Improved drogue designs, with lower diameter to length ratios, open ends, or permeable or perforated fabric ends, are more stable and less subject to snatching and tumbling, which may lead to bridle fouling. Improved drogue designs also apply forces more smoothly, and place less concentrated loads on the raft attachment points.

7.5. Ballast Systems

The following conclusions are drawn regarding water ballast systems on life rafts:

(1) Ballast bags can be made too massive for their own fabric strength, or the strength of their attachment points. Several of the references which described sea testing reported damage to large ballast bags and their attachments, although in some cases it was not clear how the damage occurred, and whether it was due to raft responses, handling, or attempting to tow the rafts in a seaway. Damaged bags lose their effectiveness as surely as damaged or bridle-fouled drogues. In general, it seems advantageous to increase bag capacity by increased planform area (length and number of bags) rather than depth. This increases lift-out force resources and provides longer attachments for strength. (Breadth of circumferential bags is limited by the diameter of the buoyancy tubes.)

(2) Although many contradictory claims have been made on all sides of the debate, there appears to be no compelling, systematic reason (anecdotal or theoretical) to conclude that there are significant hazards to raft or personnel implicit in separately bagged, toroidal, or hemispherical ballast distributions.

8. REFERENCES

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APPENDIX A: FAA LIFE RAFT REQUIREMENTS

The Department of Transportation, Federal Aviation Administration has promulgated Standards For Life rafts; Technical Standard Order TSO-C70a. Although this TSO provides minimum standard requirement for the design and construction, inflation, survivor's aids, and operational usage, it lacks specific requirements in the determination of stability, capsizing, and related testing requirements. There is thus no stringent requirement on stability or capsize resistance for U.S. aviation life rafts.

Capacity

The rated and overloaded capacities of a life raft as stated in reference 1, must be based on not less than the following usable seating areas on the floor of the life raft

- Rated Capacity - 3.6 ft^2 per person
- Overloaded Capacity - 2.4 ft^2 per person

The rated capacity of a Type I life raft may be determined by the number of occupant seating spaces which can be accommodated within the floor area, exclusive of the perimeter structure. The occupant seating area may not be less than the following size:

- The sitting area on the life raft deck may not be less than 3.0 ft^2 per person.
- The back support for each occupant not less than 14.7 inches wide and 8 inches high.
- As a part of the design and construction, at least 30% but no more than 50% of the participants must be female. (This appears to have no effect on anything.)

Our review shows that a rated capacity of 3.6 ft^2 per person is exceeded by several manufacturers. From telephone interviews with various manufacturers, we have come to the conclusion that a life raft with a rated capacity of 4.0 ft^2 which is an increase of about 11% of inside life raft space and an overloaded capacity of 3.2 ft^2 will improve the rafts behavior in adverse conditions, quite apart from occupant comfort. This means that a 20 person life raft would have 80 ft^2 of floor space at rated capacity and would carry 25 people in overload condition. On a circular floor planform, this area requirement would give a floor diameter of 10 ft, and a perimeter of almost 19 inches per occupant at rated capacity, and the required 15 inches at overload.

An adequate freeboard is also essential for the safety and survivability of the personnel onboard a life raft. A freeboard of 15 inches at rated capacity and 14 inches at overload is considered adequate and reasonable. This amount of freeboard will increase the righting energy and delay the entry of water in extreme sea conditions.

The current FAA survivor's store and equipment requirement for life rafts is considerably less than the requirement for marine life rafts. The TSO-C70a only requires the following to be included on the life raft as part of the survivor's store and equipment:

- Lights
- Accessory Case Tiedown
- Carrying Case which meets the flammability requirements of FAA standard
- A hook type knife secured by a retaining line
- One emergency locator transmitter

Capsize Phenomena & Survivability:

- There must be water pockets or other means to provide capsize resistance for an empty or lightly loaded life raft.
- Means provided for righting life raft must be such that they may be used by one person in the water.

Motions and Accelerations:

- No data or requirements

Boarding & Stability:

- Boarding aids must permit unassisted entry from the water into the unoccupied raft and must not impair either the rigidity or the inflation characteristics of the raft. Boarding handles and /or stirrups used in conjunction with boarding aids must withstand a pull of 500 lb.

- In test, ballast in the form of sand bags or equivalent may be used to achieve the required 170 lb average weight. Buoyancy must be provided by two independent buoyancy tubes. The life raft loaded to its rated capacity must have a freeboard of at least 12 inches with both buoyancy tubes at minimum operating pressure. With the critical tube deflected, it must have a freeboard of at least 6 inches. When overloaded with the critical tube deflected, it must have a measurable freeboard.

- Under static conditions and when inflated and stabilized at normal operating pressure, the pressure in the each inflatable chamber must not fall below the minimum operating pressure in less than 24 hrs. The minimum operating pressure is the pressure required to meet the minimum design buoyancy requirements.

  It must be demonstrated that the life raft is self-righting, or if not, that it can be righted by one person in water or can be boarded while inverted and still provide flotation for the normal rated capacity. The static stability of the life raft must be demonstrated when occupied at normal rated capacity and at 50% rated capacity.

Occupant Posture & Restraints:

No requirements

Shelter Characteristics:

- The life raft erected canopy must be capable of withstanding 35 knot winds and 52 knots gust in open water. The canopy must provide adequate headroom and must have provision for openings 180° apart. Means must be provided to make the openings weathertight. The canopy must be capable of being erected by one occupant of an otherwise empty raft and by occupants of a raft filled to rated capacity.

Deployment - (Release and Inflation):

- The inflation system must be arranged so that failure of one inflatable chamber or manifold will not result in loss of gas from the other chambers. Components of the inflation system must meet 49 CFR 178.37 or 49 CFR 178.44. The inflation system must be constructed to minimize leakage due to back pressure after inflation. There must be an independent inflation source for each primary flotation tube for Type I type life rafts. For emergency inflation, means readily accessible to occupants of the raft, and having a displacement of at least 32 in^3 per full stroke, must be provided to manually inflate and maintain chambers at minimum operating pressure.

- A non-rotting mooring line at least 20 feet in length must be attached at one end of the raft, with the rest of the line held to the carrying case. The breaking strength of the line must be at least 500 lb, or 40 times the rated capacity of the raft, whichever is greater, but not to exceed 1,000 lb.

- A parachute ripcord grip and retaining pocket must form the primary inflation control as part of the life raft launching equipment. When facing the release end of the carrying case, the center line of the ripcord grip retaining pocket must lie at 45° in the right upper quadrant of the end section. The line attached to the ripcord grip must serve both to retain the life raft and to actuate the gas release(s). The tension required to withdraw the static mooring line and to actuate the gas release mechanism(s) must be between 20 - 30 lb. The strength of the gas release mechanism(s), its fittings, and its attachments may not be less than 100 lb.

- The manufacturer shall determine the minimum temperature at which the complete life raft assembly with its inflation bottles, will be "rounded out" (i.e., attain its design shape and approximate dimensions) so that the life raft will be able to receive and to support the first occupant within one minute after the start of inflation.

Lifeline, Grasp Line, and Trailing Line:

- A non-rotting lifeline of contrasting color and at least 3/8-inch line diameter or 3/4-inch strap width must encircle the life raft on the outside periphery. The lifeline and its attachment must be capable of withstanding a minimum load of 500 lb.

- A grasp line, meeting the size and strength requirements for the lifeline, must be provided with sufficient slack for use by the life raft occupants.

- At least one floating heavy-trailing line not less than 75 ft length and at least 250 lb strength, must be located on the main flotation tube near the sea anchor attachment.

Performance:

- The raft must meet the seaworthiness requirement of 17 - 27 knot winds and wave heights of 6 - 10 ft. It must be capable of withstanding a saltwater marine environment for a period of at least 15 days. [In effect, due to lack of specificity, the seaworthiness criterion is of limited value.]

Sea Anchor:

- A sea anchor must be provided to maintain the raft, with rated capacity and canopy installed, on a substantially constant heading relative to the wind and have the ability to reduce the drift to 2 knots in 17 - 27 knot winds. [The broad range of wind speeds permitted makes this requirement rather soft.]

APPENDIX B: FOREIGN MARITIME AGENCIES CONSULTED

1 Australian Embassy; 202-797-3165

Dept. of Transportation:	Bill Henderson	202-797-3166
	Ms. Helen Crokran	202-797-3171
Custom Service	Ethel Gardner	202-797-3172
Defense	Sgt. Tom Lark	

2 Australian Maritime Safety Authority, P. Box 1168, Bel Connen, ACT 2616, Australia
Mr. A. X. Rosario, Area Manager
Ship and Personnel Safety Services
Tel: 61-6-279-5935
Fax: 61-6-279-5076/ 5966

3 Royal Norwegian Embassy: 202-333-6000
The Norwegian Maritime Directorate, Oslo
Tel: 47-22-454500
47-247-9900

4 DNV North America, Houston Texas
Mr. Tony Teo
Marine Safety Division
Tel: 713-579-9003

5 DNV, Oslo
Mr. Jan Kobbeltvedt
Tel: 47-67-579900
Fax: 47-67-579911

6 British Embassy: 202-462-1340, Fax: 202-898-4255
CDR Lancaster: 202-898-4583

7 Marine Safety Agency, Southampton, UK
Tel: 44-1703-329100 (main line)
Mr. Terry Clark: Tel: 44-1703-329189
Fax: 44-1703-329204

8 RINA: 44-1-235-4622
"The Naval Architect", 10 Upper Belgrave Street, London, SW1X 8BQ
Tel: 44-1-235-4622/4
Fax: 44-1-245-6959

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APPENDIX C: LIFE RAFT MANUFACTURERS INTERVIEWED

1	BFGoodrich Aerospace Aircraft Evacuation Systems 3414 S. 5th Street Phoenix, AZ 85040 Attn: David Stanton	Tel: Fax:	602-243-2200 602-243-2300
2	Eastern Aero Marine 3840 N.W. 25th Street Miami, FL 33142 Attn: Martin Schwartz	Tel: Fax:	305-871-4050 800-843-7238 305-871-7873
3	Hoover Industries 7260 N.W. 68th Street Miami, FL 33166 Attn: Marta Eriazquin	Tel: Fax:	305-888-9791 305-883-1925
4	Survival Products, Inc. 5614 S.W. 25th Stree Hollywood, FL 33023 Attn: Donna Rogers	Tel: Fax:	305-966-7329 305-966-3584
5	Winslow Marine Products Winslow Life raft Company P. O. Box 888 Osprey, FL 34229 Attn: Steve Weatherly	Tel: Fax:	813(914)-966-9791 813(914)-966-9235
6	STARK Survival Co. 6227 E. Highway 98 Panama City, FL 32404 Attn: Ken Burton	Tel: Fax:	904-871-4730 904-871-0668
7	Corporate Air Parts 6920 Hayvenhurst Avenue Suite 202 Van Nuys, CA 91406 Attn: Neil Looy/Mike Scott	Tel: Fax:	818-997-0512 818-997-0478

8	SWITLIK Parachute Company, Inc. P. O. Box 1328 1325 East State Street Trenton, N.J. 08607 Attn: Gus Fanjul	Tel: Fax:	609-587-3300 609-586-6647
9	ZODIAC of North America Inc. P. O. Box 400 Thompson Creek Road Stevensville, MD 21666 Attn: Albert Czartroyski	Tel: Fax:	410-643-4141 410-643-7269
10	BOMBARD P. O. Box 400 Thompson Creek Road Stevensville, MD 21666	Tel: Fax:	410-643-4141 410-643-4491
11	VIKING Life-Saving Equipment 1625 N. Miami Avenue Miami, Florida 33136 Attn: Poul V. Jensen Managing Director	Tel: Fax:	305-374-5115 305-374-1535
12	SMR Technologies, Inc P. O. Box 326 1420 Wolf Creek Trail Sharon Center, Ohio 44274-0326 Attn: Jim Perish	Tel: Fax:	800-858-7238 216-239-1352
13	Givens Ocean Survival Systems Co., Inc. 1 Lagoon Road Portsmouth, RI 02871 Attn: James A. Givens	Tel: Fax:	800-328-8050 401-683-7401

APPENDIX D: LIFE RAFT MANUFACTURER INTERVIEW SCRIPT

1.0 Rated capacities: 2-Man:___ 4-Man:___ 6-Man:___ 8-Man:___ 10-Man:___ 12-Man:___ 20-Man:___ Other:____

2.0 Raft planforms :
Circular :____ Hexagonal:___ Octagonal: ___
Rectangular (or rounded ends/corners):___
If rectangular, what are the approximate proportions of length to breath:______

3.0 Flotation: Single ring:___ Twin ring:___ Other :____

4.0 Canopies: None:___ Optional:___ Standard:____

If a canopy is provided, please specify:

Canopy type: Self-Erecting:____ Manual:____
Approximate canopy heights:______________________________
Approximate canopy windage areas:__________________________
Canopy material:____

5.0 Seating:
Please give the approximate seating characteristics at the raft's rated capacity. (If there is variation of these quantities between different rafts in your product line, please provide approximate ranges.)

Minimum seating area per occupant:____________________
Maximum seating area per occupant:____________________
Back support width per occupant:______________________
Seated headroom under canopy:________________________

6.0 Ballast bags or compartments (if provided):
Type and arrangement:______________________________
Total number of compartments:________________________
Total volume:______________________________________
Is there an arrangement for manually emptying the ballast compartment(s):____________________
If so, please describe:_________________________________

7.0 Raft freeboard (to top of the upper buoyancy ring):
At rated load?____
At overload capacity?____________________________________

8.0 Drogue: None:___ Optional:___ Standard:___

If a drogue is supplied with the raft, please specify:

Type:____
Size:____
Material:____

Drogue line material:_____________________________
Line size or working strength:_______________________
Standard line length of drogue line:___________________

Are lump weights or buoyant appliances provided for the drogue line?___
Description: ____________________

9.0 Stability:

Has your firm performed raft stability tests? _________________
For regulatory body approval purposes?______________________
For internal design purposes?______________________________

If tests were performed, did they include capsizing?______________
Were tests performed in waves or in still-water only:_____________

If wave tests have been performed, were breaking waves included:___
Describe:____

Please describe any special stability test procedures:_____________

If possible, please identify or describe the stability criteria which you have applied in raft design (e.g., wind forces and moments, waves, asymmetric loading): ____

10.0 Inflation system:

Type:____
Nominal inflation time:______________________________________
Inflation condition (temperature): _______________________________
Tube working pressure:_______________________________________
Mechanism to avoid premature inflation:_________________________
Relief valves:____
Topping off valves:____
Emergency pump:____

11.0 Under what regulations or criteria have your life raft(s) been approved?

USCG:___ SOLAS:___ FAA:___ USN:___

Other (please specify):______________________________

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APPENDIX E: PROPOSED CALM-WATER TESTS OF LIFE RAFTS FOR RIGHTING ENERGIES AND MOMENTS OF INERTIA

E.1 Heaving Down to Measure Righting Moments as a Function of Inclination

To measure righting arm as a function of inclination, up to the point of capsize, would be a challenging extension of the usual inclining experiment, even for a life raft of modest size. It is considered that heaving down a life raft by using loads applied to single points would produce both unrealistic deformations of the raft body, and also highly concentrated loads that would be difficult if not impossible for the fabric of the raft to withstand.

It is proposed that by rigging a pair of cargo nets (or crow's-foot bridles) in opposed directions, one over the canopy and the other under the ballast bags, with multiple attachment points distributed around opposite sides of the buoyancy rings, it would be possible to heave a raft down with a distribution of loads that would be at least fairly representative of forces in a velocity gradient, such as produced by wind or breaking wave. It is proposed that the canopy would be rigged as if at sea, with access closures (if provided) secured normally.

It is recognized that both the canopy and the ballast bags would become loaded vertically, and would tend to collapse in depth. Consequently, some change in ballast water content would tend to occur in bags below the surface as they are collapsed. However, the bags on the emerging side of the raft would be compressed less.

Measurements would include the tension in the two pendants, the angles of the pendants, and the inclination of the top of the buoyancy rings at locations midway between the pendants. These geometric and force measurements combine to give the static inclining moment.

The inclining would be done slowly to measure essentially static stability, at least to a point where flooding through the gap under the canopy begins. Thereafter, the results must be regarded as rate dependent, and therefore do not necessarily correspond to a static inclining. Three alternative approaches are possible.

(1) A standard rate of inclining can be adopted to take the raft through its range of stability in one pull, in effect taking the partial downflooding as part of the result. This may not be realistic if the selected inclining rate is much slower than in an actual capsize event, as will almost certainly be the case to allow adequate time for measurements. The progress of downflooding will keep the measurements from reaching steady state, and the raft's displacement would tend to vary over a wide (and essentially unmeasured) range.

(2) After the geometric and force measurements are taken at each inclination, the raft can be allowed to right, and the downflooding water drained or pumped. On each subsequent inclination, the raft would be heaved down to the new inclination rapidly, and the new measurements taken as quickly as possible. This is perhaps a more accurate way of doing the experiment, because it might be possible to estimate or measure the amount of downflood water removed after each pull.

(3) The raft can be allowed to downflood to equilibrium at each step in the inclining process, basically as if the canopy did not exclude flooding at all. This is probably the most repeatable procedure, but it is not clear that it represents an accurate measure of the energy available to counteract a capsize.

At some angle, a typical raft (if not statically self-righting) would reach its stability limit and capsize. The results, righting moment versus inclination, would then be integrated to the point of capsize, and the range of stability would be observed. After capsize, the cargo nets could be reversed to re-right the raft, and some idea of the energy to recover could also be gained. In addition to the measurements, videotaped observations of the deformed shape of the raft might be of some usefulness in comparing rafts.

E.2 Impulsive Inclination to Measure Inertia

The normal experimental method for estimating roll moment of inertia of a ship or craft is the sallying test, generally using weights aboard to excite roll motion, then arresting the roll excitation, and observing both the resulting natural period of roll and the extinction coefficient. From the natural roll period, and with the previous results of an inclining experiment to provide the value of the roll stiffness, the roll moment of inertia is derived.

It is doubted that a conventional sallying experiment would be able to produce useful results for a body as flexible as an inflatable life raft. The principal area of concern is that sallying would actually tend to excite flexural modes of the raft, in addition to roll, and possibly to such an extent that roll motion would be difficult to isolate. Further, if the amount of flexure is significant, it seems highly likely that roll would decay too fast to be observed accurately. In any case, significant raft flexure would lead to difficulties in interpreting the results of measurements.

Further, if the raft were tested in a confined area of water, such as a pool, or between piers, the sallying test would lead to the formation of wave reflections that would also contaminate the results.

Measurements of the raft's roll inertia other than afloat have been considered. However, it is not considered practicable to suspend a fully ballasted and loaded raft <u>in air</u> without introducing gross deformations that would make the test faulty, and possibly overstraining the raft to produce a material failure. Development of a life raft "swing-test" apparatus (basically a frame to support the raft body and ballast bag while allowing it to oscillate in roll) is considered prohibitively expensive and of limited value.

Accordingly, it is judged that the most reliable way to measure an effective roll inertia of a flexible raft, afloat, is to provide an impulsive roll moment of a known (or at least closely controlled) magnitude, and observing the raft's acceleration. This test, of course, would measure the total effective inertia of the raft, including the virtual inertia in roll. It would also include the

effects of the resulting internal flow in ballast bags, and therefore would be useful for comparison to estimated inertia values using rigid-body assumptions.

The rig for an impulsive inclination experiment is shown below. The impulse is applied by the release of a drop weight attached to a pendant which is brought just taut prior to the test. The principle is basically similar to heaving down, except that the inclining load is applied at the top of a light frame, secured to the top of the buoyancy ring(s), instead of to a cargo net or crow's-foot bridle. This lever arrangement permits an impulsive roll moment to be applied using a considerably smaller weight than would otherwise be required. The acceleration of the raft will be measured by an angular accelerometer on the frame.

The extent of roll angle produced in the inertia test need not be large, probably less than in a lift-out test. Consequently, it is considered that for an inertia test, the deformation of the raft body need not represent the raft's condition at large angles of inclination. Therefore, the fact that the vertical frame influences the distribution of inclining force is not considered an issue. The inertia of the frame, of course, would have to be deducted from the result.

In order to keep the raft from accelerating in translation, the horizontal force delivered by the drop weight is resisted by two reaction pendants on opposite sides of the raft, forming in effect the pivot points for roll. These will be rigged at approximately the height of the raft's (calculated) center of gravity. Deformation of the raft body due to moments in the horizontal plane (because of offsets between the drop weight pendant and the two reaction pendants, in plan view) are not expected to be significant if the drop weight is moderate.

E.3 Test Requirements

It is estimated that a typical inflatable raft will have a maximum righting arm of the order of the GM. Consequently, to produce the ability to heave down a raft, the force requirements should be on the order of $W\ GM / L_V$, where L_V is the typical lever arm (measured in a vertical plane) between the two opposed pendants.

L_V is approximately the depth of the raft (from the top of the buoyancy rings to the bottom of the ballast bags) at small to moderate angles of inclination. It may be assumed that the canopy will not contribute much height because it will not support a large vertical load and will tend to buckle. As inclination approaches 90 deg, the characteristic L_V should be closer to the raft diameter.

From these approximations, it is estimated that even a heavily ballasted raft can be successfully heaved down, with a force requirement of about one-fourth of its total weight with ballast and occupants.

It will be considered desirable, at least to gather an initial data set, to perform tests with rafts at various loads, from no occupants, to rated or overload capacity. It is recommended that occupant load weights be simulated using plastic sandbags, secured to the buoyancy rings. The

significance of occupant loading is not primarily the change in static conditions (weight and CG), as these can be estimated by calculation. Rather, the weight of the raft's occupants may have a very large effect on the change in <u>shape</u> of the raft as inclination increases. This is <u>not</u> easy to calculate.

The site for the test may be any of the following, assuming that the site is well-sheltered from wind, waves and current: (a) an enclosed pool; (b) a dock between finger piers; (c) a dock between a pier and a piling. The required minimum breadth of the pool or dock should be about two and a half raft breadths.

The material requirements for heaving down and impulsive inclination tests would include the following:

(1) A winch, with fairlead capable of pulling about one-fourth of the raft loaded weight, including ballast, with a maximum total distance of pull on the order of two and a half raft breadths.

(2) Load cell attachments for rigging the load cell into the heaving-down pendant between the winch and the raft.

(3) Two nets or multipart bridles, details to suit the attachment points on the raft body.

(4) Two pendants, one led to the winch, the other to a piling or padeye opposite the winch.

(5) Small line for securing the nets or bridles to the buoyancy ring.

(6) Lumber for the vertical frames for the inertia test.

(7) One drop weight, estimated to give a static heel of about 20 deg; depending on the frame height selected, this weight could be as little as two or three percent of the raft's loaded weight, including ballast water.

(8) One single block for drop weight pendant.

(9) One drop weight quick release (details TBD).

(10) Miscellaneous hardware, eyebolts, bolts/nuts/washers for frame assemblies.

Instrumentation requirements are more extensive than for the lift-out force test, but are still relatively modest. They include:

(1) Load cell

(2) Two plumb lines and graduated arcs for measuring pendant angles

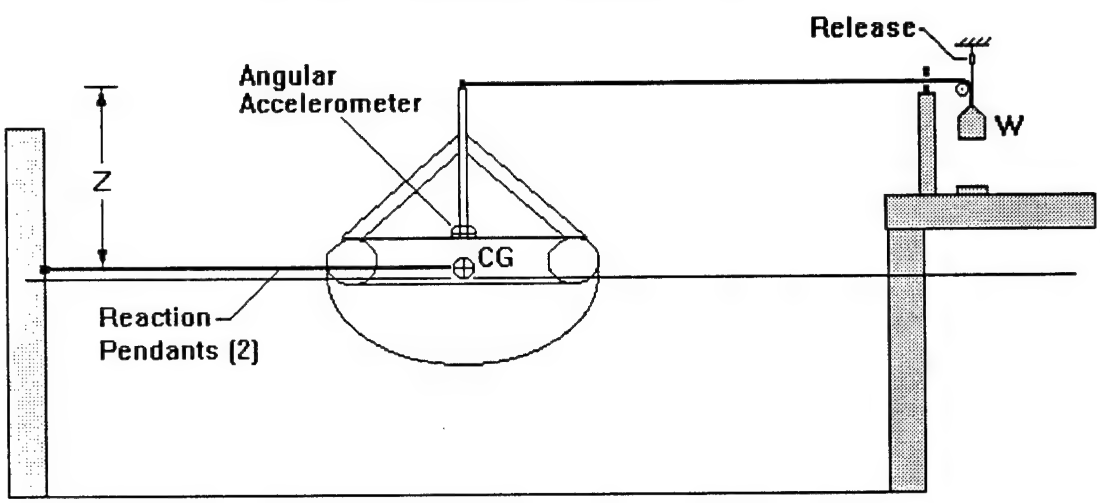
(3) Inclination potentiometer (inclinometer) for measuring raft inclination angle

(4) Angular accelerometer for inertia test

(5) Data acquisition and storage (assumed laptop PC)

In summary, it is judged that with relatively modest setup and instrumentation, not much more elaborate than the lift-out force test, still-water measurements can be taken which would give useful and direct measures of the two key elements in life raft capsize resistance: righting energy, and inertia. It is further judged that these values would be accurate enough and repeatable enough to permit the characterization of different raft designs, and to develop a database that would support analysis of capsizing experiences.

RIG FOR ROLL INERTIA EXPERIMENT



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APPENDIX F:

U.S. Coast Guard R&D Center
Marine Engineering Branch (MEB)

HC-130 Wing Life Raft Replacement Prototype

STATEMENT OF WORK

Prepared by: Robert Sedat

Date: 8/30/95

Revised by: James A. White

Date: 03/04/96

1. BACKGROUND

The Coast Guard uses HC-130 aircraft for search and rescue work, and other missions. These planes range from 5-20 years in age, and are currently undergoing a Service Life Extension Program which will probably enable their use for an additional 20-30 years. The planes are presently equipped with two (and sometimes four) 20 person inflatable life rafts, mounted in the wings. The rafts are deployed automatically (but have a manual backup), and are attached to a tether line to prevent drifting. The present life rafts do not have modern heat sealed seams or water filled ballast bags.

2. SCOPE

It is desired to develop a prototype system to replace the existing F2B life rafts on the HC-130 with water ballasted life rafts having heat sealed seams - referred to hereafter as the "prototype F2B replacement life raft". This system will incorporate those features described in Section 4. REQUIREMENTS of this SOW. It is intended to be a drop-in replacement for the existing life rafts, requiring no modifications to the existing airframe and life raft release system.

3. APPLICABLE DOCUMENTS

3.1 Military Specification, MIL-L-9131H, Life Rafts, Inflatable, Twenty Man (GFI).

3.2 DOT 1700.18B, Acquisition, Dissemination and Publication of DOT Scientific and Technical Reports (GFI).

4. REQUIREMENTS

4.1 Task 1: Prototype Development

4.1.1 The contractor shall design, manufacture and deliver one water ballasted prototype F2B replacement life raft for the existing F2B HC-130 life raft system complete and ready for use. The prototype F2B replacement life raft shall be manufactured from commercial grade fabric or equivalent, and all seams shall be heat sealed.

4.1.2 The prototype F2B replacement life raft shall have a capacity for 20 persons, have a canopy and inflatable canopy supports, and be weighted to promote upright deployment. The

capacity of the life raft shall be calculated using FAA requirements, i.e. 3.6 square feet of space and 250 pounds of buoyancy per person. It shall have provision for stowage of survival equipment (see ATTACHMENT B). The raft shall be capable of being righted from the upside down position in the water by a 160 pound person. The canopy shall be furled upon deployment to minimize sail area and drifting. The raft shall be equipped with an automatically-deployed drogue to minimize drifting, and a heaving line to facilitate rescue. The drogue and heaving line shall be attached to the raft in the stowed condition, so that they are already attached to the raft in the deployed condition.

4.1.3 The prototype F2B replacement life raft shall have two, separate, horizontal, inflatable, buoyancy chambers (or tubes), and be equipped with a CO_2 inflation system. The raft shall also be equipped with weighted, water-fillable ballast chambers. Both buoyancy chambers shall inflate, and the ballast chambers fill with water, automatically upon deployment. Each buoyancy chamber shall be equipped with a readily accessible topping off valve, to provide for make up air if required. Each of the two buoyancy chambers shall have sufficient buoyancy to support a full load, i.e. 20 persons, the survival equipment, canopy, and other equipment, e.g. sea anchor, heaving line, painter line, etc.

4.1.4 The raft shall be automatically deployable, with a manual backup system, and shall be equipped with a fail-safe device to prevent accidental inflation and deployment during in flight conditions with altitude variations between sea level and 50,000 feet above sea level. The raft shall deploy tethered to the plane with a painter line which allows a maximum of 10 feet of drift after reaching the water. One end of the painter line shall be attached to the raft in the stowed condition, so that it is already attached to the raft in the deployed condition. The line shall be of sufficient tensile strength to hold the raft in moderate seas, but designed to break in the event that the aircraft sinks. The contractor shall demonstrate that the system provided addresses the concerns expressed in this paragraph.

4.1.6 The stowed raft, CO_2 inflation system, and all onboard supplies, shall fit in the government furnished mock-up of the HC-130 wingwell (See Attachment A).

4.1.7 In order to insure that the prototype F2B replacement life raft is manufactured to standards that are equal to, or better than, those applying to the present F2B life raft, the prototype shall comply with the following sections of Applicable Document 3.1, as amended herein:

APPLICABLE SECTIONS OF MIL-L-9131H.

"3.0 REQUIREMENTS. Page 4 of MIL-L-9131. The following sections under 3.0 REQUIREMENTS shall apply."

"3.4 Design and construction. Page 5 of MIL-L-9131H. The following sections and subsections of 3.4 Design and construction shall apply."

"3.4.1 Cut edges. Page 5 of MIL-L-9131H. This section shall apply if, and as, applicable to the material used in the fabrication of the prototype F2B replacement life raft."

"3.4.5.1 Inflatable tubes. Page 6 of MIL-L-9131H. This section shall apply if, and as, applicable to the prototype F2B replacement life raft."

"3.4.8 Carrying case. Page 7 of MIL-L-9131H. Delete the section as written and substitute, "A suitable carrying case shall be fabricated for the prototype F2B replacement life raft."

"3.4.10.1 LRU-15/A raft. Page 7 of MIL-L-9131H. Delete the section as written and substitute, "The prototype F2B replacement life raft shall have provision for the storage of the survival equipment, type and quantity, as listed in ATTACHMENT B of the HC-130 Wing Life Raft Replacement Prototype SOW."

"3.6 Performance inspections. Page 8 of MIL-L-9131H. The following sections and subsections of 3.6 Performance inspections shall apply."

"3.6.1 Operation (carbon dioxide). Page 8 of MIL-L-9131H. Delete, "... as shown in Drawing 63A80H1 ...". Delete references to cemented attachments if not applicable to the prototype F2B replacement life raft."

"3.6.2 Pressure. Page 8 of MIL-L-9131H. Delete references to cemented attachments if not applicable to the prototype F2B replacement life raft."

"3.6.3.1 Raft inflatable tubes. Page 9 of MIL-L-9131H. This section shall apply as written."

"3.6.3.2 Inflatable floor support. Page 9 of MIL-L-9131H. This section shall apply if, and as, applicable to the prototype F2B replacement life raft."

"3.6.4 Weight. Page 9 of MIL-L-9131H. Change ".. 90 pounds." to ".. approximately 110 pounds." in the last sentence of this section.

APPLICABLE SECTIONS OF MIL-L-9131H - Continued.

"3.6.5 <u>Strength of attachments</u>. Page 9 of MIL-L-9131H. This section shall apply if, and as, applicable to the prototype F2B replacement life raft. It is the intention of this specification that the attachments in the prototype F2B replacement life raft be as strong as those in the F2B life raft."

"3.6.6.1 <u>Seam breaking strength</u>. Page 9 of MIL-L-9131H. This section shall apply as applicable to heat sealed seams. It is the intention of this specification that the seams in the prototype F2B replacement life raft be as strong as those in the F2B life raft."

"3.8 <u>Workmanship</u>. Page 11 of MIL-L-9131H. This section shall apply as written."

"4. QUALITY ASSURANCE PROVISIONS. Page 11 of MIL-L-9131H. The following sections of 4. QUALITY ASSURANCE PROVISIONS shall apply."

"4.6 <u>Inspection conditions</u>. Page 14 of MIL-L-9131H. The following sections and subsections of 4.6 <u>Inspection conditions</u> shall apply."

"4.6.1 <u>Atmospheric conditions</u>. Page 14 of MIL-L-9131H. Delete, "...711.2 to 812.8 mm (28 to 32 inches)...", from the first sentence and replace it with, "...762 ± 51 mm (30 ± 2 inches) of mercury...".

"4.6.1.1 <u>Temperature correction</u>. Page 14 of MIL-L-9131H. This section shall apply as written."

"4.6.1.2 <u>Barometric pressure correction</u>. Page 14 of MIL-L-9131H. This section shall apply as written."

"4.6.2 <u>Pressure measurement</u>. Page 14 of MIL-L-9131H. This section shall apply as written."

"4.6.3 <u>Inspection area and equipment</u>. Page 15 of MIL-L-9131H. This section shall apply as written."

"4.6.4 <u>Air</u>. Page 15 of MIL-L-9131H. This section shall apply as written."

"4.7 <u>Inspection methods</u>. Page 15 of MIL-L-9131H. The following sections of 4.7 <u>Inspection methods</u> shall apply."

"4.7.1.1 <u>Life rafts</u>. Page 15 of MIL-L-9131H. Delete the section as written and substitute the following."

"The prototype life raft shall be visually examined for both critical and minor defects, by the Contracting Officer's

APPLICABLE SECTIONS OF MIL-L-9131H - Continued.

Technical Representative at the contractor's facility, to determine conformance to this specification. The classification and list of defects given in table IV, as applicable, shall be used to classify and enumerate the defects found. If the prototype has any critical defect it shall be considered to be unacceptable. Minor defects shall be repaired."

"4.7.2 Operation (carbon Dioxide). Pages 15 & 16 of MIL-L-9131H. Applicable sections shall apply. The test shall be performed on the floor or a table in the contractor's facility. It is the intention of this specification that the prototype F2B replacement life raft meet the time and pressure requirements of this section."

"4.7.3 Pressure. Page 16 of MIL-L-9131H. Applicable sections shall apply. It is the intention of this specification that the prototype F2B replacement life raft meet the time and pressure requirements of this section."

"4.7.4 Leakage. Pages 16 & 17 of MIL-L-9131H. Applicable sections shall apply. It is the intention of this specification that the prototype F2B replacement life raft meet the time and pressure requirements of this section."

"4.7.6 Weight of the raft. Page 17 of MIL-L-9131H. This section shall apply as written."

"4.7.9 Seam breaking strength. Page 18 of MIL-L-9131H. Delete the first sentence of this section and insert the following. "The contractor shall heat seal two pieces of the life raft material (using the same method as used in the fabrication of the life raft) so as to make a seam that is perpendicular to the warp of the material and at least 20 inches long. Ten (10) rectangular strips, 2 inches wide and 12 inches long shall be cut from this sample for tensile testing by the government (at the discretion of the government). The 12 inch cut shall be made along the warp, and be perpendicular to the seam. The seam shall be at the middle of the 12 inch long sample."

"5. PACKAGING. Page 18 of MIL-L-9131H. Replace the requirements of MIL-L-9131H with the following sentence. "The prototype life raft shall be properly stowed in the carrying case and then packaged in a container suitable for shipment, and shipped, to USCG R&D Center, Groton, CT without damage."

"Table IV. Classification of defects for visual examination of the life raft. (See 4.7.1.1) Pages 24, 25, 26, and 27 of MIL-L-9131H. Sections applicable to the prototype F2B replacement life raft shall apply."

APPLICABLE SECTIONS OF MIL-L-9131H - Continued.

This concludes the applicable sections of MIL-L-9131H.

4.2 Task 2: Demonstration.

The contractor shall demonstrate the deployment of the prototype F2B replacement life raft from the government furnished mock-up C-130 aircraft wingwell described in Attachment A in a suitable swimming pool convenient to the contractors facility. Any failures to deploy correctly shall be noted and corrected. A record shall be maintained of the number of times that the life raft deployes in an upright position. The contractor shall prepare 5 copies of a brief letter report conforming to Applicable Document 3.1 which fully describes the prototype life raft and documents the deployment test results.

5. Government Furnished Equipment.

The government shall furnish one mock-up of the C-130 aircraft wingwell described in Attachment A.

6. Schedule

Task	Days after award
Fabricate Prototype	150
Complete Demonstration	180
Modify Prototype (if required)	240
Repeat Demo. (if required)	270

ATTACHMENT A

FABRICATION OF MOCKUP C-130 AIRCRAFT WINGWELL
(Taken from NAVAIR 13-1-6.1)

3-43. To fabricate a mockup C-130 aircraft wingwell to aid in packing LRU-15/A liferafts, proceed as follows:

Materials Required

Quantity	Description	Reference Number
As Required	Locally Available Material	(Not Applicable)

NOTE

The following steps concern fabrication of a mock wingwell assembly for use during shop folding/packing of the liferaft. However, the liferaft may be accordion-folded into the new liferaft container directly in the aircraft wing should the mockup assembly not be desired.

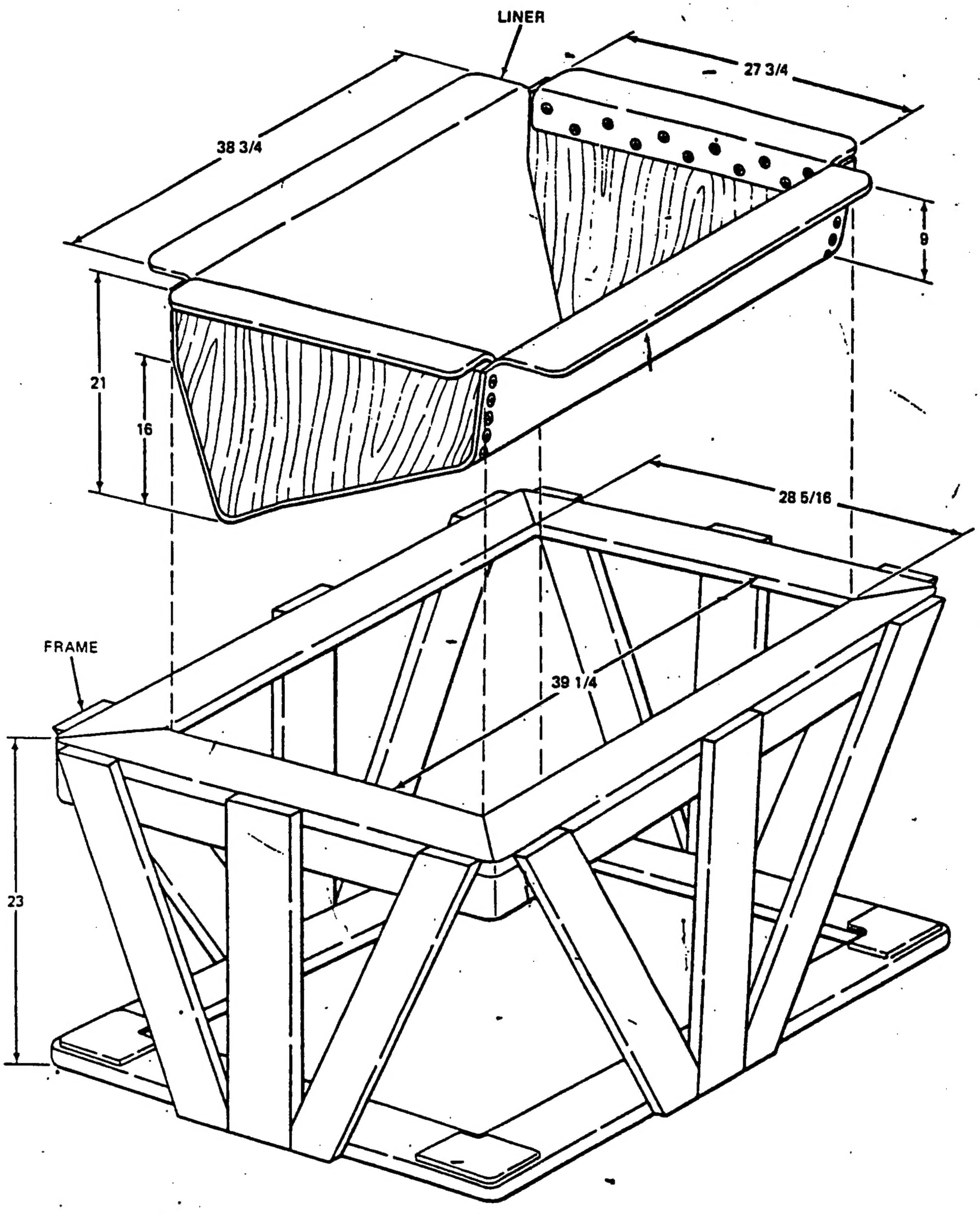
1. Using available materials, construct a packing assembly as outlined in figure 3-13. Using any suitable fastening devices, fasten liner flush with top of frame. Ensure that all edges are smooth and burrs are removed to prevent damage to liferaft. Use tape or equivalent nonabrasive material, whenever necessary, to smooth rough edges.

2. Fabricate a CO_2 cylinder cradle from available materials. (A spare CO_2 cylinder will be helpful in obtaining correct dimensions.) Allow provisions for left- and right-hand cylinder installations. Edges should be protected with tape or equivalent.

NOTE

Spare aircraft components (fiberglass liner and CO_2 cradle) may be used if available in place of locally fabricated parts.

ATTACHMENT A (Continued)



MATERIAL: 1" X 4" PINE SHELVING OR EQUAL

61-425

Figure 3-13. Packing Frame Assembly

ATTACHMENT B

LIST OF SURVIVAL ITEMS FOR THE PROTOTYPE F2B REPLACEMENT LIFE RAFT (Taken from USCG Aviation Computerized Maintenance System Mandatory Special Requirements 025.0 Rev'd 04/15/95 Page 1 of 23 F2B Wing Life Raft Build-Up.)

Item	NSN	Quantity
Adapter, Pump	4220-00-092-5823	1
Bag, Water Storage	8465-00-485-3034	4
Chord, Type I Nylon	4020-00-240-2154	50 ft.
Chord, Type III Nylon	4020-00-240-2146	15 ft.
First Aid Kit, Rigid	6545-00-922-1200	3
Knife, Pocket	5110-00-162-2205	1
Light, Chemical Wand, 6 inch	6260-01-074-4229	2
Light, Marker, SDU-5E	6230-00-938-1778	1
Lipstick, Anti-Chap (Cold)	6508-00-116-1479	10
Flare, Mk-13	1370-00-309-5028	4
Flare, Mk-79 Pengun	1370-00-309-5027	2
Mirror, Signal	6850-00-105-1252	2
Mylar Space Blanket	7210-00-935-6667	6
Pump, Hand	4320-00-097-4580	1
Rations	8970-01-028-9405	10
Reverse Osmosis Pump (Survivor-35)	Commercial Purchase	1
Sea Dye Marker	6850-00-270-9986	2
Sponge, Bailing	7920-00-240-2555	2
Sunburn Preventative (Minimum 30 SPF)	Commercial Purchase	2
Water, Flex Pack	8960-01-124-4543	24
Whistle, Plastic	8465-00-254-8803	1

Note: This list carries a later date than MIL-L-0131H and is therefore considered to be more in line with current practise.